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SECTION 7

ALTERNATING-CURRENT GENERATORS

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7.1 INTRODUCTION

This section deals with ac electric machines that convert mechanical power into electrical power. Such generators can be either synchronous generators or induction generators. Rotational speed of a synchronous generator is exactly at a speed that is synchronized with the ac power frequency, and this rotational speed is kept constant with varying loading conditions. Rotational speed of an induction generator is slightly above synchronous speed, and this rotational speed varies slightly with varying loading conditions. Induction generators find their major power generation application in wind turbine power generation. Synchronous ac generators dominate present-day commercial power generation by fossil fuels, nuclear reactors, and hydraulic turbines. All discussions of ac generators in this section are focused upon synchronous generators.

AC synchronous generators range in size and capability from very modest machines that are rated at a few hundred watts to the largest machines that are rated at 2000 MW. This section is intended to provide a general understanding of the nature of ac synchronous generators of this size and capability. Most discussions are focused upon larger synchronous generators with ratings above 10 MW.

This section is not intended to serve as a guide to design or manufacture of these generators, and it is not intended to serve as a textbook that explains details of the theory of function of these machines. A few textbooks about generator design and theory that may be of interest to readers of this handbook are listed in the bibliography of this section.

7.2 BASICS OF MACHINE CONSTRUCTION AND OPERATION

7.2.1 Machine Morphology

All synchronous generators function as magnetic energy conversion devices to convert mechanical power into electrical power by means of magnetic fields. The input torque provided by the prime mover (the turbine) is balanced by the magnetic torque between the stationary and rotating structures in the generator.

Several different approaches are possible to accomplish this power conversion function. For the larger synchronous generators that are primarily discussed in this section, the magnetic fields are

typically established by electrical currents circulated in stationary ac windings, and rotating dc windings, and these magnetic fields are circulated within the generator through highly permeable steel structures. In such a generator, the ac winding is electrically connected to an electrical power system and physically mounted on the stationary member of the generator (the stator), and the dc winding is electrically connected to a dc power source and physically mounted on the rotating member of the generator (the rotor). Because of the prevalence of polyphase power generation, distribution, and utilization, the ac winding in all but the smallest synchronous generators is generally a polyphase winding. The most common number of phases is three.

All larger synchronous generators include an ac armature winding and a dc field winding. The electromagnetic interaction of these two windings provides the basis for ac power generation. In some of the smallest synchronous generators, with ratings below a few hundred kilowatts, the magnetic function of the dc field winding is provided by permanent magnets. In all large synchronous generators, the dc field is provided by a dc field winding. This section is limited to discussions of generators, with an ac armature winding and a dc field winding.

In most large synchronous generators, the ac armature winding is located on the stator of the machine, and the dc field winding is located on the rotor, as illustrated schematically in Fig. 7-1. An important exception is a special synchronous generator that is generally known as a brushless exciter. A brushless exciter is a relatively small synchronous generator (50 to 500 kW) that is used to provide dc electric current to the rotating field winding of a large synchronous generator. In brushless exciter, the dc field winding is mounted on the stator and the armature winding is mounted on the rotor. That said, all further discussions of morphology in this section are based upon the most common arrangement for generators of 10 MW and above, where the ac armature winding is located on the stator of the machine and the dc field winding is located on the rotor, as illustrated in Fig. 7-1.

In a generator, like that illustrated in Fig. 7-1, the magnetic circuit consists of a steel stator core that is mounted upon the steel stator case and a steel rotor that is supported on bearings that are either set into the case or separately mounted to the foundation. The coils of the armature winding are mounted in the stator core, and the coils of the field winding are mounted on the rotor. Armature winding electrical coils for generators of the type shown in Fig. 7-1 are typically deployed in radial slots formed in the inner diameter of the stator, and field winding electrical coils are typically deployed in radial slots formed in the outer diameter of the rotor, as illustrated in Figs. 7-2 and 7-3 respectively.

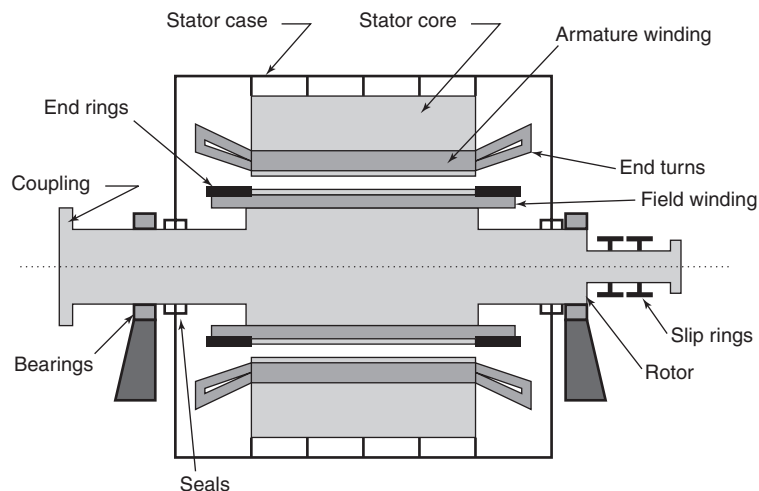


FIGURE 7-1 Elements of an ac generator.

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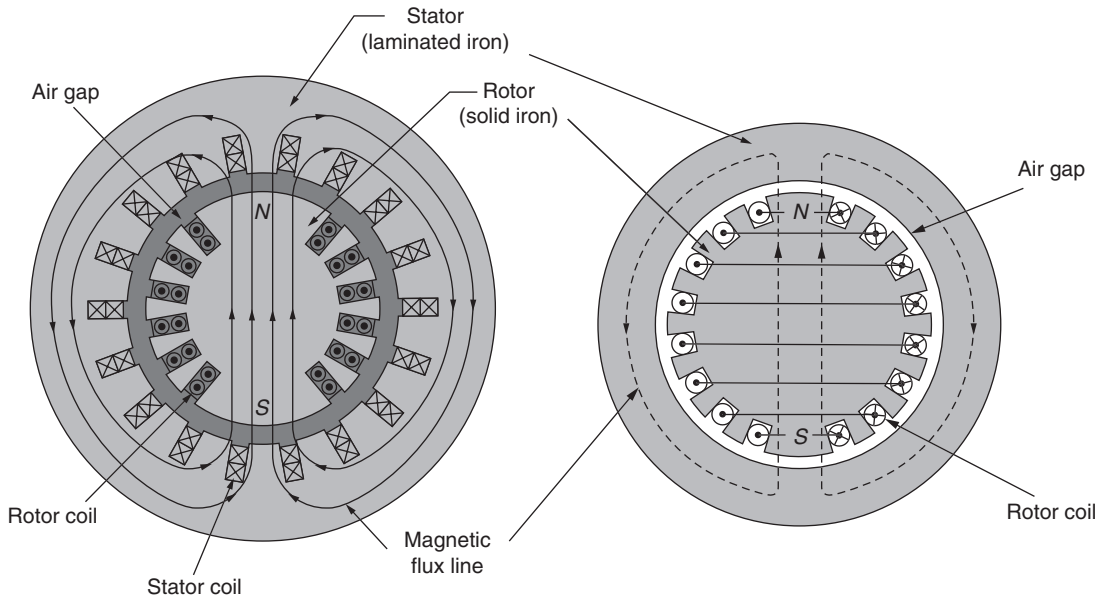


FIGURE 7-2 Round-rotor generator with two poles.

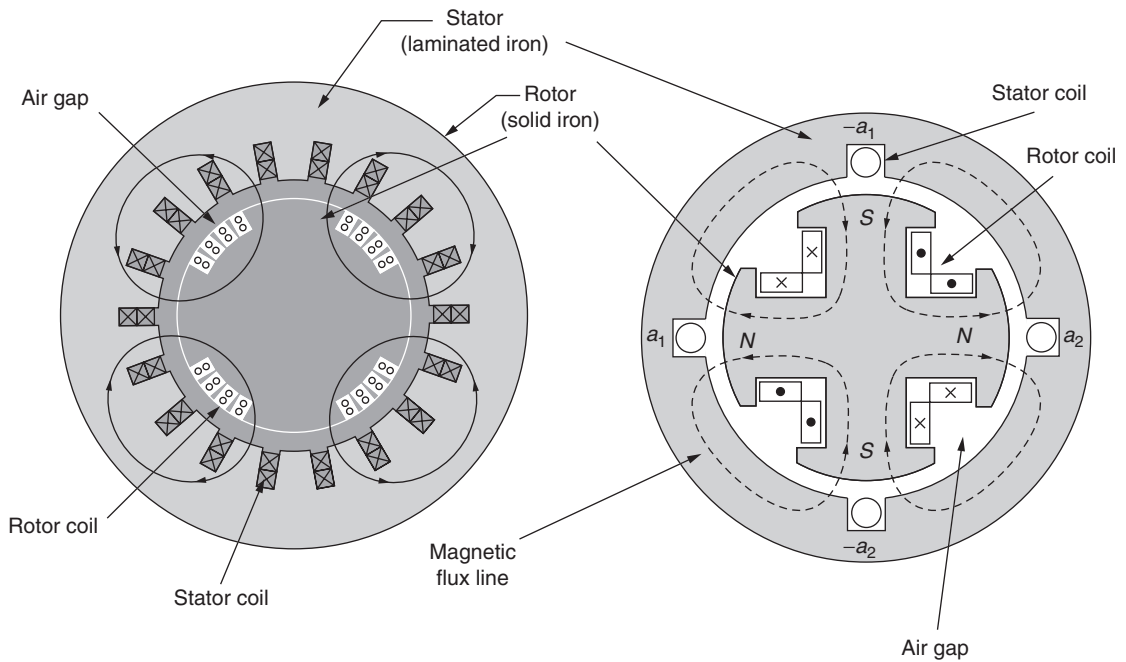


FIGURE 7-3 4-pole generator (left is round rotor, right is salient pole).

7.2.2 Poles and Frequency

The rotor and stator (field and armature) of a synchronous machine must have the same number of poles, as the magnetic interaction is between a succession of north-south magnetic-field pole pairs. The number of pole pairs for a machine will be noted as p . The relationship between electrical frequency f_e and mechanical speed N is

$$f_e = p \frac{N}{60} \quad (7-1)$$

where f_e is measured in hertz (Hz) and N is in revolutions per minute (r/min). A common expression for Eq. 7-1 is

$$N \cdot P = 120 \cdot f_e \quad (7-1a)$$

where P is number of poles (not number of pole pairs).

Synchronous generators are built in two elementary forms:

- *Round-rotor* machines are constructed with a rotor consisting of a cylinder of magnetic steel. In modern generators, the cylinder is formed from a single forging of vacuum degassed steel. The field winding is contained in radial slots in the surface of the rotor. Round-rotor machines usually have two or four poles as illustrated in Figs. 7-2 and 7-3 respectively. The diameter of the rotor of a typical 25-MW generator is about 700 mm. The diameter of a 2000-MW generator can approach 2 m.
- *Salient-pole* machines are constructed with a number of pole pieces mounted to a central rotor shaft. The rotor pole pieces can be solid steel or assemblies of steel plates that are bound together axially with bolts. The diameter of the rotor can range from less than 1 m in smaller salient pole generators to nearly 20 m in the largest hydroelectric generators.

In both round-rotor and salient-pole generators, the magnetic flux passing through the rotors does not vary in time, and the magnetic flux passing through the stator core does vary periodically in time at the electrical line frequency. Consequently, the rotors can be made of solid steel, but the stator cores must be made of thousands of thin layers of highly permeable electrical steel. Each layer of stator core steel is coated with a thin layer of electrical insulation.

For electric utility operation, in which generation takes place at 50 or 60 Hz, mechanical speed is inversely proportional to the number of poles. Thus, 2-pole machines, which turn at 3000 or 3600 r/min, are used for most fossil-(fuel)-fired steam turbine generators which require high shaft speeds. Most nuclear steam turbine generators, which have a lower shaft speed requirement, employ 4-pole designs and therefore turn at 1500 or 1800 r/min. Turbine generators for both fossil and nuclear power plants are typically round-rotor designs.

Hydroelectric generators, which typically have much lower shaft speeds than turbine generators and consequently require a large number of poles, are generally built as salient-pole machines. This is true also for generators intended for operation with large reciprocating engines, such as medium-speed diesels.

7.2.3 Basis of Operation

A synchronous generator works by causing an interaction of two multiple-pole magnetic-field distributions, those of the stator (armature) and, rotor (field). The interaction is said to be *synchronous* because, if the rotor is turning at the speed described by Eq. (7-1), the armature and, rotor magnetic fields are turning at the same physical speed. The synchronous operation may be described in two elementary ways, referred to as the magnetomotive force (mmf) *method* and the *flux method*. These are described here, assuming a simple, linear, round-rotor model for the machine. It should be noted that this model will, of necessity, be modified later to fully understand operation of the machine.

MMF Method. A principal feature of a synchronous generator is the mutual inductance between phases. Assuming a 3-phase machine, the mutual inductances between the field winding and the 3-phase windings are

$$M_{af} = M \cos p\phi \quad (7-2)$$

$$M_{bf} = M \cos \left(p\phi - \frac{2\pi}{3} \right) \quad (7-3)$$

$$M_{cf} = M \cos \left(p\phi + \frac{2\pi}{3} \right) \quad (7-4)$$

where M is the peak value of mutual inductance and ϕ is the angle between the axes of the field winding and the stator phase winding designated a . If it is further assumed that phase-phase inductances, both self- and mutual, are not a function of rotor position, the use of energy methods gives a simple expression for machine torque:

$$T = -pMi_a i_f \sin p\phi - pMi_b i_f \sin \left(p\phi - \frac{2\pi}{3} \right) - pMi_c i_f \sin \left(p\phi + \frac{2\pi}{3} \right) \quad (7-5)$$

If the rotor turns at a constant angular velocity $\omega p = 2\pi f_e/p$, the field current is held constant at a value of I_f and the three stator currents are sinusoids in time, with the same amplitude and with phases that differ by 120°

$$p\phi = \omega t + \delta_i \quad (7-6)$$

$$i_a = I \cos \omega t \quad (7-7)$$

$$i_b = I \cos \left(\omega t - \frac{2\pi}{3} \right) \quad (7-8)$$

$$i_c = I \cos \left(\omega t + \frac{2\pi}{3} \right) \quad (7-9)$$

torque is

$$T = -\frac{3}{2} pMI_f \sin \delta_i \quad (7-10)$$

Note that torque is proportional to the product of the two current amplitudes and to the sine of the phase angle between the current distributions. Further, the torque is acting in a direction so as to align the two current distributions.

Flux Method. The flux method for estimating machine torque focuses on voltage (and hence flux) induced in the machine stator. If L_a is phase self-inductance and L_{ab} is phase-phase mutual inductance, flux linked by armature phase a is

$$\lambda_a = L_a i_a + L_{ab} i_b + L_{ab} i_c + MI_f \cos p\theta \quad (7-11)$$

Noting that the sum of phase currents is, under balanced conditions, zero and that the mutual phase-phase inductances are equal, this is

$$\lambda_a = (L_a - L_{ab}) i_a + MI_f \cos p\theta = L_d i_a + MI_f \cos p\theta \quad (7-12)$$

where L_d denotes synchronous inductance.

This flux is described by the equivalent circuit of Fig. 7-4, where

$$E_{af} = j\omega MI_f e^{j\delta} \quad (7-13)$$

and δ is the phase angle between *internal* voltage E_{af} and *terminal* voltage V , and $X_d = \omega L_d$.

Assume $R_a \ll X_d$, where R_a is the armature resistance.

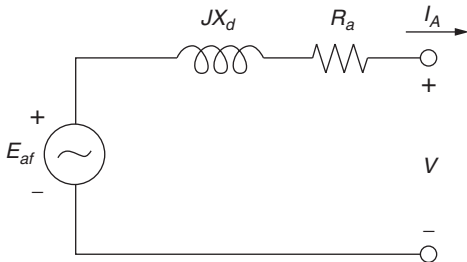
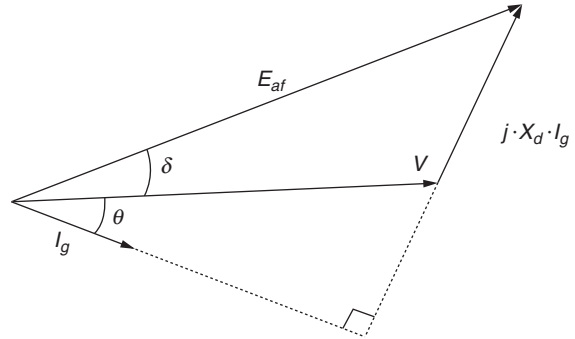
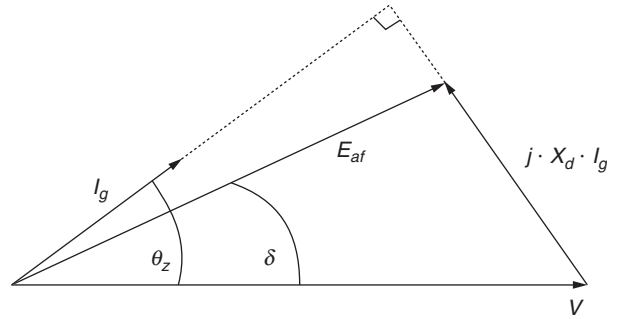


FIGURE 7-4 Steady-state equivalent circuit (R_a is neglected for analysis).



(a) Overexcited (lagging power factor).



(b) Underexcited (leading power factor).

FIGURE 7-5 Round-rotor synchronous generator.

If the generator is connected to a voltage source (i.e., if V is fixed), terminal current is

$$I = \frac{V - E_{af} e^{j\delta}}{jX_d} \quad (7-14)$$

Real and reactive power into the terminals of phase a are

$$P_a = -\frac{1}{2} \frac{VE_{af}}{X_d} \sin \delta \quad (7-15)$$

$$Q_a = \frac{1}{2} \frac{V^2}{X_d} - \frac{1}{2} \frac{VE_{af}}{X_d} \cos \delta \quad (7-16)$$

Considering all three phases, total generated power is

$$P = -3P_a = \frac{3}{2} \frac{VE_{af}}{X_d} \sin \delta \quad (7-17)$$

Phasor diagrams illustrating the operation of a round-rotor synchronous generator are shown in Fig. 7-5. When the machine is *overexcited*, terminal current *lags* terminal voltage. When the generator is *underexcited*, terminal current *leads* terminal voltage.

7.2.4 Salient-Pole Machines: Two-Reaction Theory

Salient-pole generators, such as hydroelectric generators, have armature inductances that are a function of rotor position, making analysis one step more complicated. The key to analysis of such

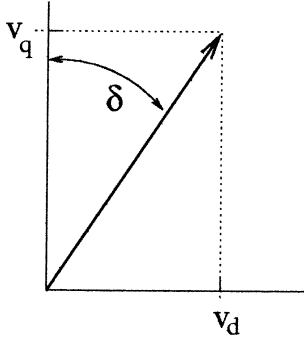


FIGURE 7-6 Direct- and quadrature-axis voltages.

machines is to separate mmf and flux into two orthogonal components. The two components are aligned with the direct axis and the quadrature axis of the machine (Fig. 7-6). The direct axis is aligned with the field winding, while the quadrature axis leads the direct by 90°. Then, if ϕ is the angle between the direct axis and the axis of phase a , flux linking phase a is

$$\lambda_a = \lambda_d \cos \phi - \lambda_q \sin \phi \quad (7-18)$$

Then, in steady-state operation, if $V_a = d\lambda_a/dt$ and $\phi = \omega t + \delta$, we obtain

$$V_a = -\omega\lambda_d \sin \phi - \omega\lambda_q \cos \phi \quad (7-19)$$

or

$$V_d = -\omega\lambda_q = V \sin \delta \quad (7-20)$$

$$V_q = \omega\lambda_d = V \cos \delta \quad (7-21)$$

One might think of the *voltage* vector as leading the *flux* vector by 90°. If the machine is linear, fluxes are given by

$$\lambda_d = L_d I_d + M I_f \quad (7-22)$$

$$\lambda_q = L_q I_q \quad (7-23)$$

Note that, in general, $L_d \neq L_q$, and for wound-field machines, $L_d > L_q$. Terminal voltage now has these components

$$V_d = -\omega\lambda_q = -\omega L_q I_q = V \sin \delta \quad (7-24)$$

$$V_q = \omega\lambda_d = \omega L_d I_d + \omega M I_f = V \cos \delta \quad (7-25)$$

which is easily inverted to produce

$$I_d = \frac{V \cos \delta - E_{af}}{X_d} \quad (7-26)$$

$$I_q = -\frac{V \sin \delta}{X_q} \quad (7-27)$$

where $X_d = \omega L_d$, $X_q = \omega L_q$, and $E_{af} = \omega M I_f$.

In the complex frame of reference

$$V = V_d + jV_q \quad (7-28)$$

$$I = I_d + jI_q \quad (7-29)$$

complex power is, in the sense of a generator

$$P + jQ = -\frac{3}{2} VI^* = -\frac{3}{2} \{(V_d I_d + V_q I_q) + j(V_q I_d - V_d I_q)\} \quad (7-30)$$

or

$$P = \frac{3}{2} \left[\frac{VE_{af}}{X_d} \sin \delta + \frac{V^2}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\delta \right] \quad (7-31)$$

$$Q = -\frac{3}{2} \left[\frac{V^2}{2} \left(\frac{1}{X_q} + \frac{1}{X_d} \right) - \frac{V^2}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \cos 2\delta - \frac{VE_{af}}{X_d} \cos \delta \right] \quad (7-32)$$

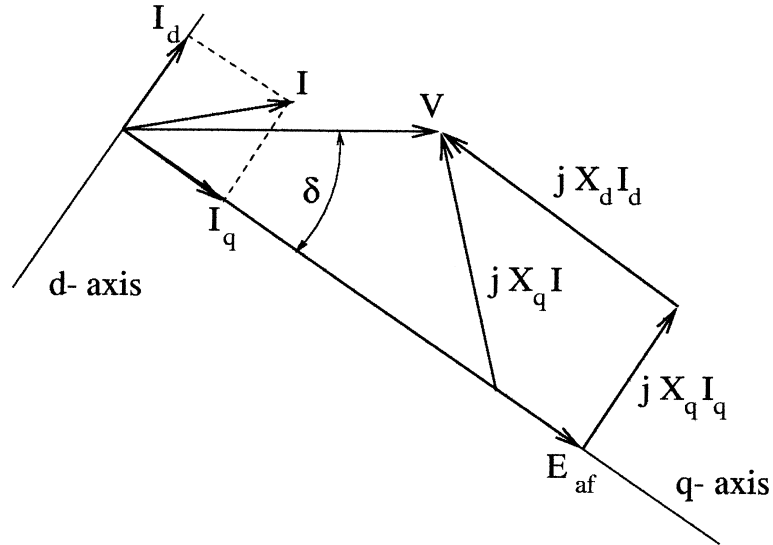


FIGURE 7-7 Vector diagram for salient-pole machine.

Figure 7-7 shows a phasor diagram for a machine with “positive” saliency (and ignoring stator resistance). It is helpful to note that in such a machine, a vector with complex amplitude jIX_q begins along the quadrature axis and ends at the ends of the terminal voltage vector.

7.2.5 Machine Size and Utilization

Generators produce torque through interaction between magnetic flux density and current over the surface of the stator, and reaction torque through the same type of interaction over the surface of the rotor. The stator and rotor face each other across the air gap. Power produced is

$$P = \omega_{\text{mech}} T = 2\pi \frac{f}{p} T = 2\pi \frac{N}{60} T \quad (7-33)$$

where torque produced is

$$T = 2\pi R^2 l \sigma \quad (7-34)$$

where f = electrical frequency, Hz

N = mechanical speed, r/min

R = stator inner radius

l = active length

σ = average value of air gap shear stress, given approximately by

$$\sigma \approx \frac{1}{\sqrt{2}} B_1 K_z \quad (7-35)$$

where B_1 is the peak value of fundamental magnetic flux density at the stator surface and K_z is the effective surface current density root mean square (rms) of the armature. The effective surface current density is ampere-turns per unit of periphery, modified by pitch and distribution factors, and by power factor.

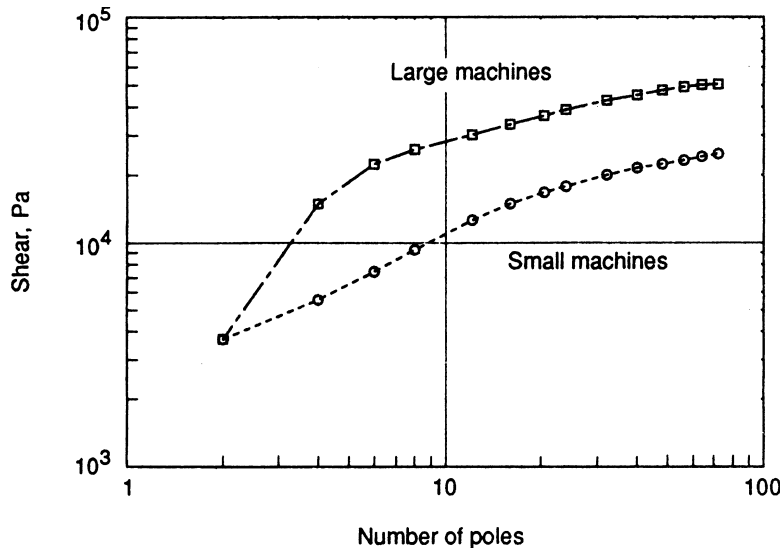


FIGURE 7-8 Typical shear stress, salient-pole, air-cooled generators.

Shear stress normally increases with pole pitch for a particular voltage and number of poles because the deeper armature slots and greater field coil space allow more ampere-conductors per unit of periphery. Typical shear stress levels for indirectly cooled, salient-pole generators are shown in Fig. 7-8. Shear is higher for directly cooled machines and a consequence of increased current density, as shown in Fig. 7-9.

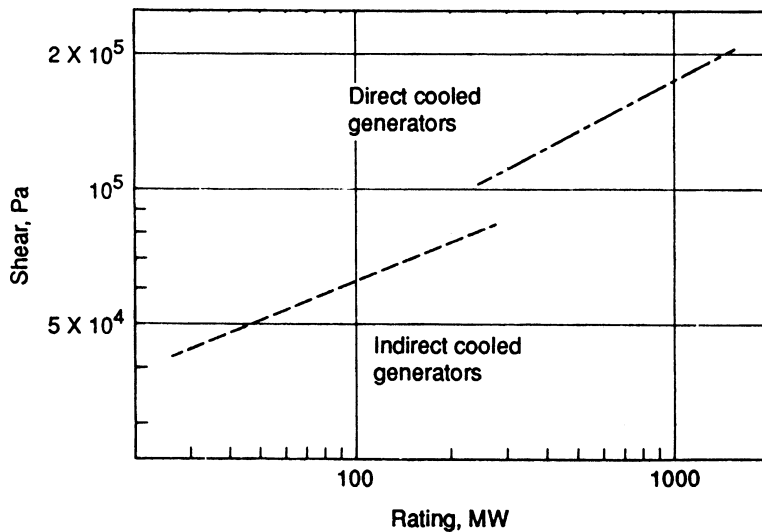


FIGURE 7-9 Typical shear stress, high-speed generators.

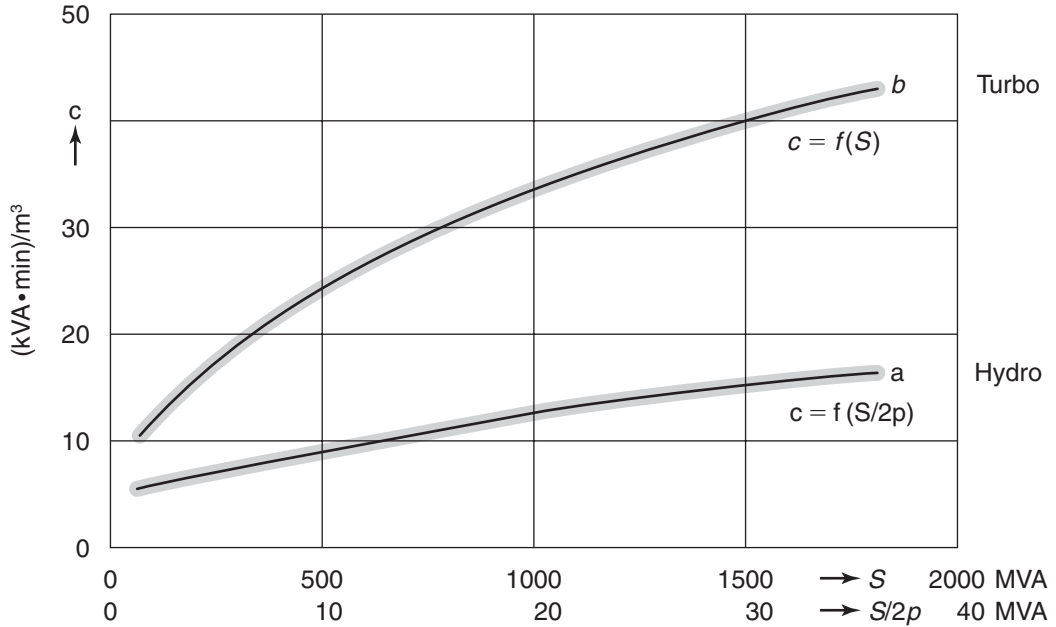


FIGURE 7-10 Utilization factors. (ABB.)

Another rough estimate of machine size employs the *utilization factor*:

$$c = \frac{S}{D^2 l N} \quad (7-36)$$

where S is machine rating, D and l are outside diameter and length, respectively, and N is rotational speed. Typical values for the utilization factor c are shown in Fig. 7-10. Here the utilization factor depends on unit rating (high-speed machines) or unit rating per pole (low-speed machines) and on cooling.

7.3 ELECTROMAGNETICS

Sketches of the major elements of synchronous generators, together with field “flux forms,” are shown in Figs. 7-11 and 7-12. Here the generator is “unrolled” and shown as if the air gap were flat. Note that the main flux distribution air gap is not exactly sinusoidal. Thus the voltage produced will contain time harmonics. Assign C_n to be the amplitude of the n th-space harmonic of the flux density, relative to the peak amplitude B_0 .

The fundamental flux per pole is

$$\Phi_1 = \frac{2RlB_0C_1}{p} \quad (7-37)$$

7.3.1 Generated Voltage

The rms amplitude of generated voltage is, for the time, fundamental

$$V_1 = \frac{1}{\sqrt{2}} \omega N_a k_w \Phi_1 \quad (7-38)$$

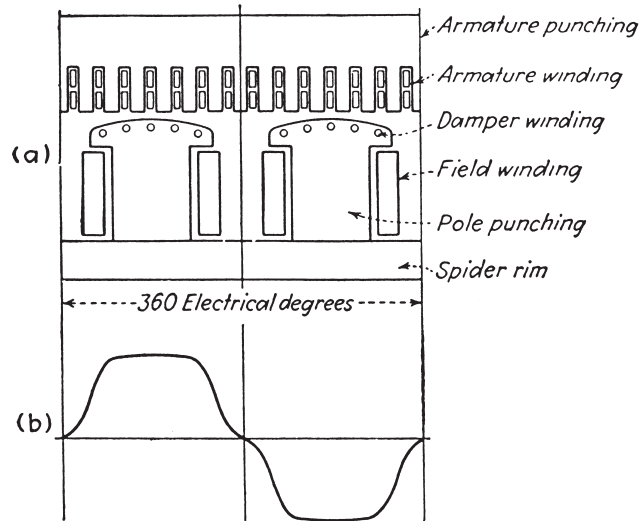


FIGURE 7-11 (a) Generalized sketch of one pair of poles for a salient-pole machine; (b) flux form for typical pair of poles (current in field winding only).

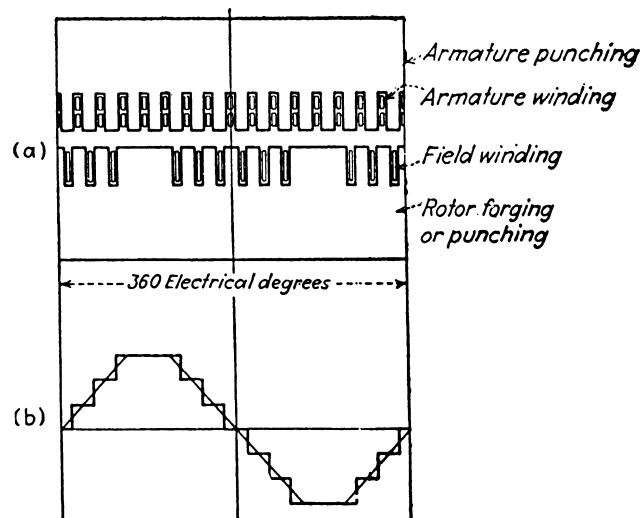


FIGURE 7-12 (a) Generalized sketch of one pair of poles for cylindrical rotor machine; (b) flux form for a typical pair of poles (current in the field winding only).

where V_1 is the time fundamental voltage induced in a phase and N_a is the number of turns in the phase. In a 3-phase machine connected in wye, line-line voltage is $\sqrt{3}$ times phase voltage. The winding factor k_{wn} is explained in Eqs. (7-40) through (7-42).

Harmonics. Time-harmonic voltages will be induced, and they are

$$V_n = V_1 \frac{C_n k_{wn}}{C_1 k_w} \quad (7-39)$$

It should be noted that certain time harmonics, those referred to as the *triplen* harmonics (odd factors of 3), are induced in all three phases of a 3-phase machine in phase. Thus, if line-line voltage is measured, these harmonics (orders 3, 9, 15, . . .) will turn out to have zero amplitude.

Tooth Ripple Effects. The voltage waveform predicted in Eq. (7-39) neglects the effect of armature teeth and slots on the air-gap flux. The resulting modulations of the air-gap fields do not generate voltages in armature conductors directly, rather induce currents in the field winding, any damper windings that may exist, and in the rotor body itself and slot wedges. These currents produce flux components, which in turn produce voltages in the armature winding. The orders of these voltages are the integer multiple of the number of slots per pole pair, ± 1 . Thus, in a winding with 24 slots per pole pair, the harmonics will have orders of 23, 25, 47, 49, 71, 73, and so on.

Estimation of voltage waveform is actually quite complex. While Eq. (7-39) may be used for a first-order estimate, manufacturers of generators typically use numerical (finite element) methods for prediction of harmonic voltage production in actual practice.

Load Effects. Load on the machine affects the harmonic content in the following ways:

1. Increased field current tends to increase all internal voltages including harmonics.
2. Armature reaction generally reduces the fundamental voltage more than the harmonics and, through tooth and slot permeance variations, introduces additional harmonics.
3. Magnetic saturation changes harmonic magnitudes.
4. The fraction of harmonic *internal voltage* that appears at the machine terminals depends on the relationship between internal and load impedance.

Voltage Waveform Standards. There are two ways of specifying the nonideal (departure from a sine wave) nature of a voltage waveform. Both of these are defined in ANSI C42.10. Limiting values for these factors are specified in ANSI C50.12, C50.13, and C50.14.

Deviation Factor. This is, as the name implies, the maximum deviation from a sine wave. It is defined as the maximum difference between the actual waveform and the equivalent sine wave, normalized to the equivalent sine wave amplitude.

Telephone Influence Factor. This is a weighted sum of the magnitudes of all harmonics in the voltage waveform. The weighting of each harmonic is intended to reflect the relative objectional effect of inductive coupling at each harmonic frequency on telephone communications.

Pitch and Breadth Factors. The winding factor is $k_{wn} = k_{pn} k_{bn} k_{sn}$. Its component parts are called the *pitch factor*

$$k_{pn} = \cos \frac{n\alpha}{2} \quad (7-40)$$

the *breadth factor*

$$k_{bn} = \frac{\sin \frac{m n \gamma}{2}}{m \sin \frac{n \gamma}{2}} \quad (7-41)$$

and, when applicable, the *skew factor*

$$k_{bn} = \frac{\sin \frac{n\theta_s}{2}}{\frac{n\theta_s}{2}}$$

where $\alpha = \text{pitch angle}$: the electrical angle between coil halves of the armature winding (this is generally a bit less than π to reduce the impact of higher harmonics and to make armature end windings shorter)

m = number of slots per pole per phase

γ = electrical angle between slots

θ_s = electrical angle of skew

Here, the relevant angles are stated in *electrical* terms. The electrical angle is p times the physical angle. Thus, in a 4-pole machine with 72 slots, the electrical angle between slots is $2 \times 360/72 = 10^\circ$.

In many ac generators, the skew angle is zero for which the skew factor is unity. In some cases, the stator is skewed with respect to the rotor (or vice versa) to reduce the effects of slot openings in inducing currents in rotor parts with a consequent effect on rotor surface losses and noise.

7.3.2 Example of 4-Pole, Armature-Wound Machine

As an example, consider a 4-pole armature wound in 48 slots with a 5/6 relative pitch. The *coil pitch*, or the number of slot pitches between coil halves, is then 10 slots ($5/6 \times 48/4$). The number of slots/pole/phase is 4 ($48/[2 \times 2 \times 3]$). Then the winding factors for the first few harmonics are

Harmonic	k_p	k_d	k_w
1	0.9659	0.9577	0.9250
5	0.2588	0.2053	0.0531
7	0.2588	-0.1576	-0.0408
11	0.9659	-0.1261	-0.1218
13	-0.9659	0.1261	-0.1218
17	-0.2588	0.1576	-0.0408
19	-0.2588	-0.2053	0.0531
23	-0.9659	-0.9577	0.9250
25	0.9659	-0.9577	-0.9250
29	0.2588	-0.2053	-0.0531
31	0.2588	0.1576	0.0408
35	0.9659	0.1261	0.1218
37	-0.9659	-0.1261	0.1218

Observe that the winding factors k_w for the harmonics 23 and 25 have the same value as the fundamental voltage. This is so for all harmonics whose numbers are equal to (integer multiple of number of slots per pair of poles) ± 1 . These harmonics are called slot harmonics, and the armature winding cannot attenuate the voltages induced by flux waves of these orders.

7.3.3 Armature Reaction

Current in the armature conductors produces an mmf which has the same number of poles as the field structure. The fundamental harmonic of this mmf rotates at synchronous speed, and adds to the field mmf in a vector sense as shown in Fig. 7-13. For generators supplying reactive current to an inductive load, the net effect of the armature reaction is to oppose the field mmf, requiring additional field current to sustain flux.

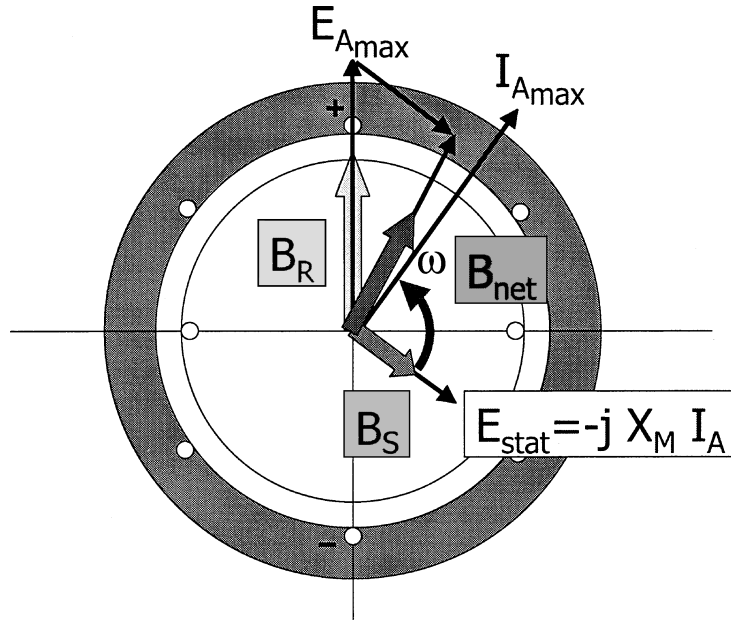


FIGURE 7-13 Armature reaction (vector analysis of magnetic fields).

The peak value of the space fundamental of armature reaction current for a 3-phase machine is

$$F_a = \frac{3}{2} \frac{4}{\pi} \sqrt{2} N_a I k_p k_b k_s \quad (7-43)$$

where I is rms terminal current, N_a is the number of series turns per phase, and the winding factors are as defined above.

Space harmonic components of armature reaction current can produce losses in the rotor as they turn asynchronously. The magnitude of the harmonic mmf of order n is

$$F_{an} = \frac{3}{2} \frac{4}{n\pi} \sqrt{2} N_a I k_{pn} k_{bn} k_{sn} \quad (7-44)$$

The rotational speed of each of these harmonics is

$$\omega_n = \mu_n \cdot \omega \quad (7-45)$$

where, for a 3-phase machine, the rotational direction is same as that of the fundamental (positive) for harmonics of orders 7, 13, 19, ..., and is opposite from the rotation of the fundamental (negative) for harmonics of orders 5, 11, 17, The electrical frequency of the pairs of these waves in the rotor frame turns out to coincide, so that the armature harmonics of orders 5 and 7 and fundamental frequency both appear in the rotor frame at 6 times the fundamental frequency.

7.3.4 Magnetic Circuit and Material

The magnetic circuit of an ac generator, as with other electric machines, is made up of the air gap, the stator teeth and backiron, the rotor poles, and the shaft section. Each of these elements has an effect on machine rating and operation.

The function of the magnetic circuit is to carry flux that links the armature conductors to produce voltage.

Air gap. The air gap constitutes the division between the rotating part of the machine—the rotor, which carries the field winding—and the stationary part of the machine—the stator, which carries the armature winding. In ac generators, the air-gap dimension is determined by the electrical characteristics of the machine. There is a trade-off between excitation mmf (toward a small air-gap dimension) and armature reaction flux (toward a large air-gap dimension). This trade-off generally results in an air gap, which is substantially larger than mechanical considerations such as machining tolerances or windage loss would dictate.

Stator Teeth and Backiron. The armature magnetic circuit carries alternating flux and is always laminated, either with complete ring laminations (for small machines) or with overlapping segmented laminations. The material most commonly used is sheet steel, of an alloy containing about 3.5% silicon, in sheets of thickness between about 0.35 and 0.65 mm. Grain-oriented steel, with reduced losses and improved permeability in the direction of rolling, is often used in large turbogenerators. Orientation in the circumferential direction is advantageous in such machines because of the large proportion of steel and moderate flux densities in the backiron. At high flux densities characteristic of the armature teeth, the advantage of grain orientation becomes less pronounced.

The active region of the armature constitutes the alternation of stator teeth and slots carrying the armature winding. The division between teeth and slots is a compromise between flux-carrying capability and current-carrying capability. The trade-off generally results in a division that is about half slots and half teeth. Flux densities in the stator teeth are usually high enough to result in moderate saturation of the magnetic material.

Rotor Iron. The magnetic flux in the rotor is nearly constant, varying in the main only slightly with changes in load and terminal voltage and with small higher frequency components due to time and space harmonics of armature flux. This allows the rotor magnetic circuit to be made of solid steel.

In turbine generators, the rotor is typically made of a single-piece forging of steel with slots for the field winding cut by machining. The losses caused by harmonic driven eddy currents in the solid steel pole faces can be problematic, and are reduced by making the air gap larger, by increasing the number of stator slots and, by choosing a suitable (short-pitch) coil throw for the armature.

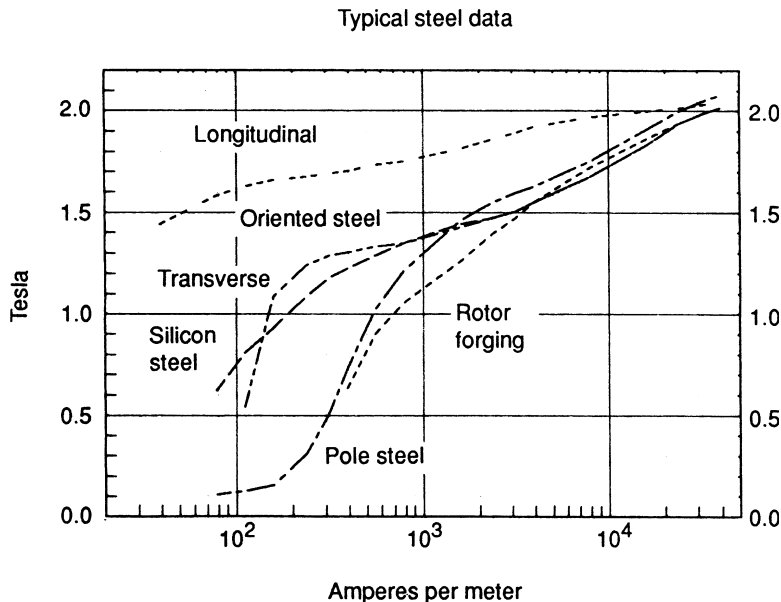


FIGURE 7-14 Magnetization curves of commonly used steels.

Salient-pole machines may have solid or laminated poles. In many cases, laminated poles are necessary to control eddy current losses. Pole laminations are commonly made of low carbon steel, 1.5 to 2 mm thick. Thinner steel, sometimes with silicon content, may be used where further control of eddy current losses is required. The shaft, or inner portion of the rotor of salient-pole machines, is often a solid forging, or in large machines such as hydroelectric generators may be fabricated from structural steel pieces.

Magnetic Materials. Typical magnetization characteristics of steel materials used in the magnetic circuit of ac generators are shown in Fig. 7-14.

7.4 MACHINE OPERATION

In normal operation, real power is dictated by the prime mover and reactive power is determined by the real power and by field current.

7.4.1 Capability Diagram

Equations (7-31) and (7-32) are approximate ways of estimating the real and reactive power output of a generator as a function of field current and torque angle. (Eq. 7-46 is provided for additional clarification.) If these are cross-plotted as shown in Fig. 7-14, a way of representing the capability of an ac generator emerges as shown in Fig. 7-15. This is called a *capability chart* for obvious reasons and four limits are shown.

$$P = 3 \cdot V_\phi \cdot I_A \cdot \cos(\theta_z) = 3 \cdot V_\phi \left(\frac{E_A \cdot \sin(\delta)}{X_s} \right)$$

$$Q = \left(\frac{3 \cdot V_\phi}{X_s} \right) \cdot X_s \cdot I_A \sin(\theta_z) = 3 \cdot V_\phi \cdot I_A \sin(\theta_z) \quad (7-46)$$

The final capability curve is shown in Fig. 7-16. Four limits are shown on this chart:

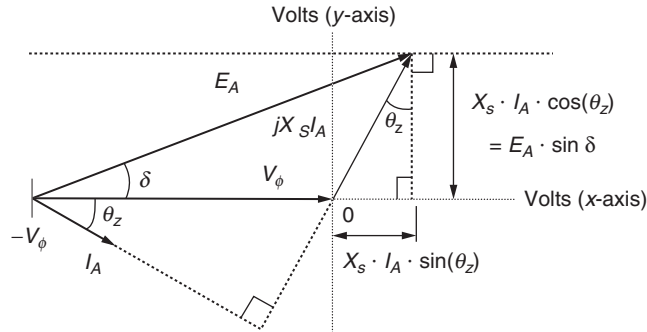
1. The field winding limit is generally related to the thermal capability of the field winding, and limits operation of the generator at high reactive power conditions.
2. The armature winding limit is generally related to the thermal capability of the armature winding, and is typically a limit on total kVA (kilovoltampere) output of the machine.
3. The stability limit is related to torque angles that are nearly at the peak of the torque-angle curve (90° for round-rotor machines).
4. Often, the configuration of magnetic flux is such that, at high reactive power absorption (negative Q), there is axial flux in the core ends, leading to excessive heating and limiting the reactive power that can be absorbed by the machine.

Very often the prime-mover power rating is plotted on the capability chart. It is, of course, a line of constant real power. The heating related limits (armature, field, and core end) may be functions of the state of the cooling system of the machine, such as hydrogen pressure. (See Sec. 7.10 on cooling.)

7.4.2 Saturation Curves and Excitation

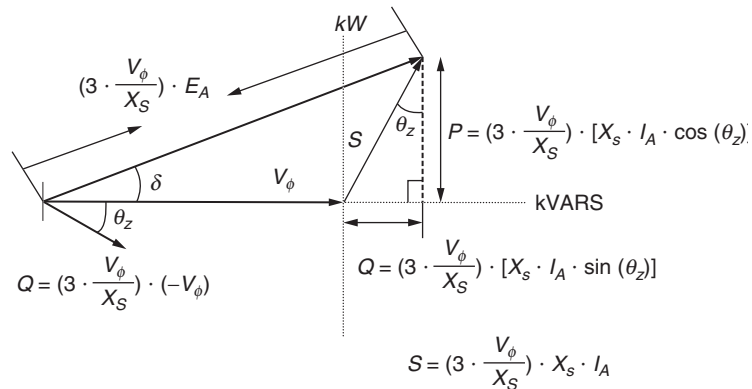
Alternating-current generators are usually operated with at least part of the magnetic circuit partially saturated, so that the linear model of machine operation implied by some of the foregoing discussion does not give exactly the right answers. What follows is an approximate way of estimating excitation requirements for an ac generator.

It should be noted that numerical methods, employing finite elements, are now available and capable of making even more accurate estimates of machine performance including excitation

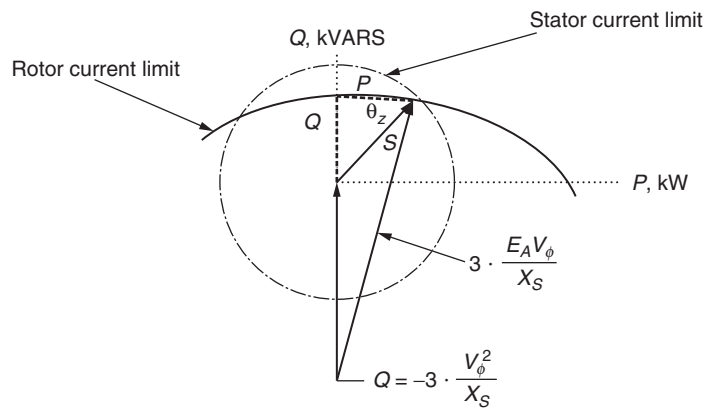


$$\text{Note: } I_A \cos(\theta_z) = \frac{E_A \cdot \sin \delta}{X_S}$$

(a) Developing the capability curve from the phasor diagram.



(b) Relating Power and Reactive Power to the phasor diagram.



(c) Relating the phasor diagram to the capability curve.

FIGURE 7-15 Estimating the real and reactive power of a generator as a function of field current and torque angle.

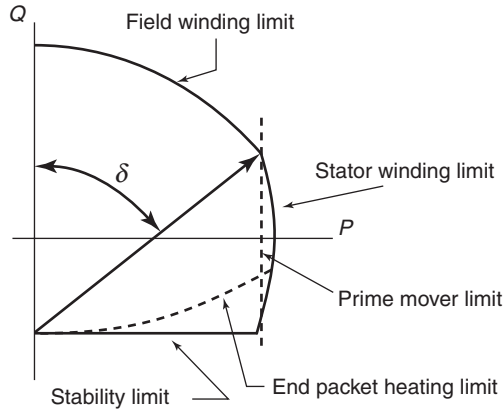


FIGURE 7-16 Capability diagram, round-rotor machine.

requirements. When these more sophisticated methods are available, it is generally better to use them. The approximate method described here is included for two reasons: (1) because it may aid in a physical understanding of generator operations and (2) because it gives reasonably accurate answers without the need for a large number of computer “cycles.”

Figure 7-17 shows open- and short-circuit characteristic curves for an ac generator. These curves are taken with the generator operating at rated speed. Important curves are

1. The air gap line is the extrapolation of open-circuit voltage versus field current at low levels of field current.
2. The no-load saturation curve is the actual open-circuit voltage versus field current characteristic.
3. The short-circuit saturation curve typically does not show saturation. It represents a measurement of current in the terminals of the generator, with the terminals short-circuited, versus field current.
4. The rated current, zero power factor saturation curve shows voltage at the terminals of the machine versus field current if the machine is operated with rated armature current at zero power factor.

Calculating Excitation Requirement. Field current required for machine operation consists of three parts

$$I_f = I_{FG} + I_{FSI} + I_{FS} \quad (7-47)$$

where, I_{FG} is the field current required to excite the air gap, I_{FSI} is the field current required to compensate for direct-axis armature current, and I_{FS} is the field current required to compensate for saturation. Note that this method does not account for saturation of the quadrature axis. Armature resistance is generally neglected.

Addition of the three components of current is shown in Fig. 7-18. In this figure, the field current that compensates for armature reaction is added at the power factor angle θ . The current I_{FS} is the current required to compensate for direct axis saturation. I_{FS} is the distance from the air-gap line to the no-load saturation curve at the voltage corresponding to the flux level in the magnetic circuit. This voltage is referred to as the voltage behind Potier reactance. It is estimated as shown in Fig. 7-19.

To find the (fictitious) Potier reactance, refer back to Fig. 7-17. Note that for the zero power factor test, all the fluxes are on the direct axis, so they add directly. Two of the current components, I_{FG} and I_{FSI} , are easily determined. The difference between field current for the zero power factor test and the sum of these two currents is I_{FS} . Since this corresponds to the distance between the air-gap

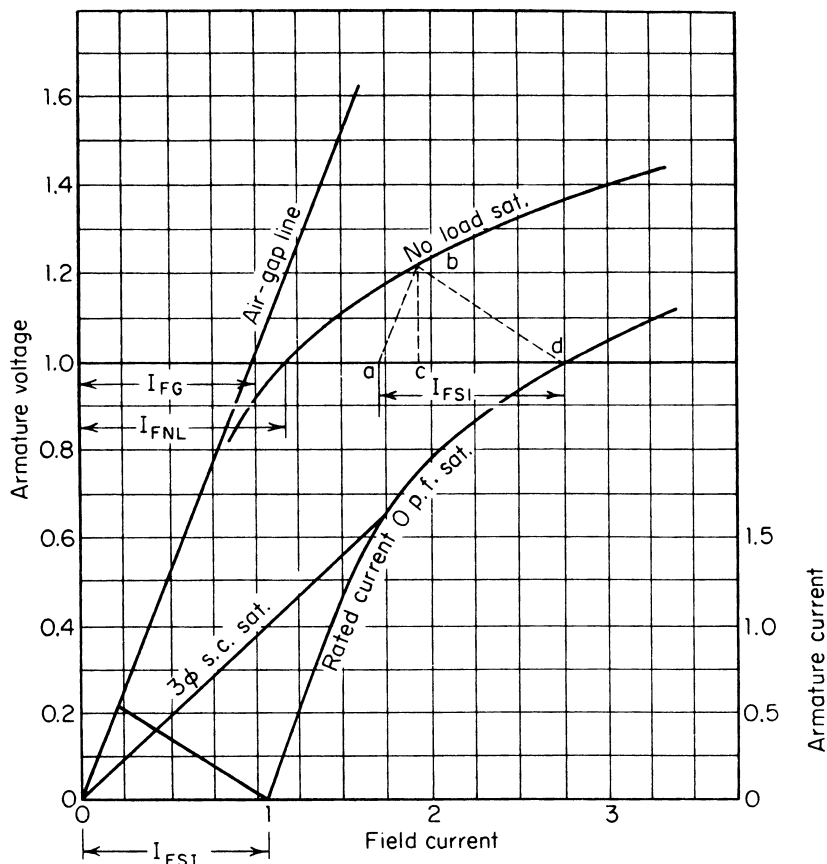


FIGURE 7-17 Typical saturation curves of an ac generator showing graphic determination of Potier reactance (quantities are in per unit values).

line and saturation curve at the voltage behind Potier reactance, it determines that voltage. For the zero power factor test, $I_a x_p$ is a vertical line of length x_p since $I_a = 1$. The distance between the saturation curve and air-gap line is the same as I_{FS} at a voltage found by casting a line parallel to the air-gap line from $I_F - I_{FSI}$. This is ab on Fig. 7-17. Then x_p corresponds to bc on the same figure.

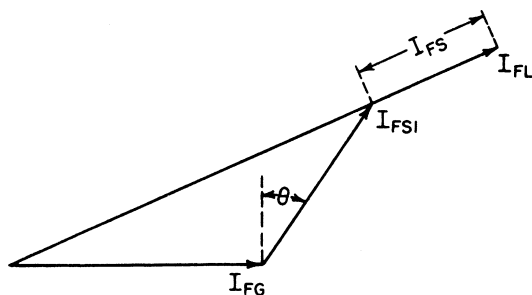


FIGURE 7-18 ANSI method of calculating load excitation.

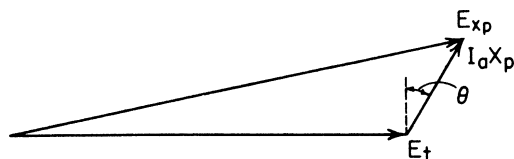


FIGURE 7-19 Calculation of voltage behind Potier reactance.

7.5 ARMATURE WINDINGS

A wide variety of winding types may be used to produce a desired voltage with the desired number of phases and a suitable waveshape. In small generators, “scramble wound” armature windings may be used. However, in most alternator applications, double-layer, form-wound coils in open slots with 60° phase belts are used. In such a winding, each slot has two conductor bars (often called *half-coils*), not necessarily from the same phase winding. These bars are insulated from ground and secured in the slot, usually by wedges. It is usually necessary for the bar to have the ability to slide axially in the slot to accommodate thermal expansion, but it must not be loose in either the radial or azimuthal directions. This has led to a number of proprietary techniques for armature construction.

7.5.1 Winding Forms

Figure 7-20 shows an example winding diagram. For the purposes of this figure, the machine is shown “rolled out flat,” with the dotted lines on either side representing the same azimuthal location. In this case, the machine has 24 slots, each with two half-coils, as shown in the slot allocation section of the drawing, at the bottom of the figure. The upper part of the figure shows how one phase of the winding would be laid out. This drawing shows a lap type winding (the most commonly used) with a $\frac{5}{6}$ pitch. In a 24-slot, 2-pole winding a full-pitch coil would span 12 slots, while in the $\frac{5}{6}$ pitch winding the coils span 10 slots.

Fractional Slot Windings. Fractional slot windings, in which the number of slots per pole per phase is not an integer, have coil groups that differ from one another. These can be arranged to produce balanced voltages under circumstances that are beyond the scope of this discussion.

7.5.2 Stranding and Transposition

At power frequencies (50 or 60 Hz), the skin depth in copper is on the order of 1 cm so that it is usually necessary to subdivide armature conductors into a number of parallel strands. In form-wound

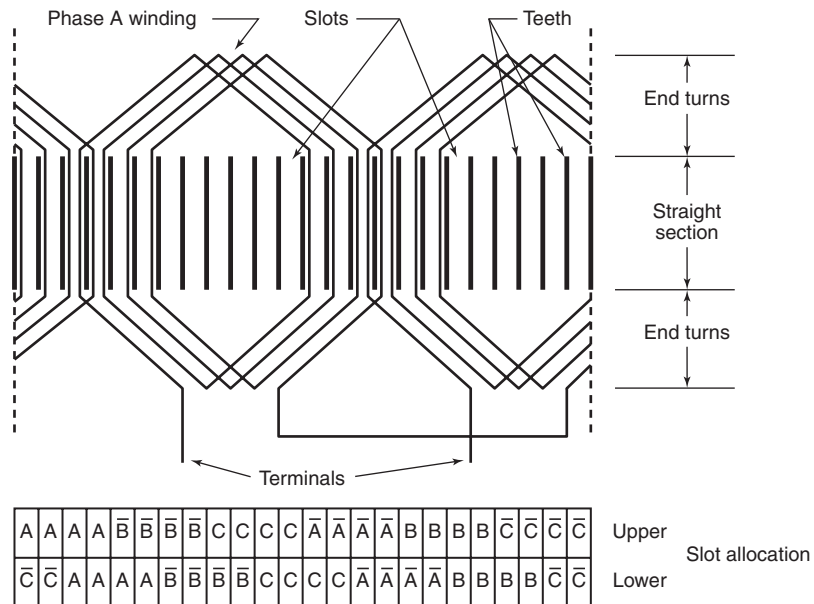


FIGURE 7-20 Armature in 24 slots, $\frac{5}{16}$ pitch.

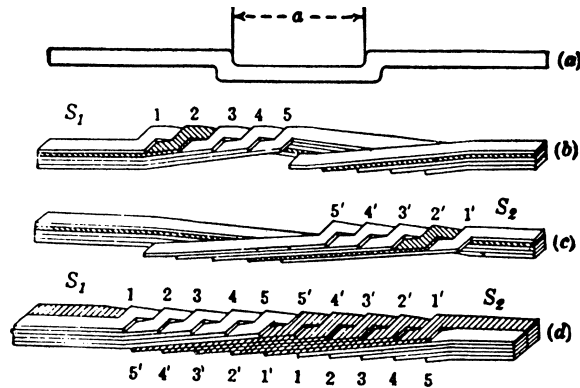


FIGURE 7-21 Illustration of Roebel transposition: (a) typical offset conductor strand; (b) group of conductor strands composing half the conductor; (c) complementary group; (d) assembly.

coils, these strands are usually rectangular to allow for good space factor. To prevent circulating currents between parallel strands, it is necessary to employ transposition to ensure that voltages induced in each strand are approximately the same.

The simplest form of transposition, often used in transformers and sometimes in generators, is to twist the armature conductors at 180° in the end turns. Or sometimes, groups of conductors are connected together in the end turns with a progressive transposition that constitutes a “twist” of the winding from half-coil to half-coil.

Transposition of strands in the end turns is generally not satisfactory in large ac generators. A transposition scheme attributed to Roebel is usually used (see Fig. 7-21). The Roebel transposition is equivalent to a twist of the conductors in the slot. It is usual to carry out the Roebel transposition only within the slot part of the winding. A variety of transpositions are used, including 180° , 360° , and 540° . The first two are effective only at eliminating circulating currents due to flux crossing the slot, but do not compensate for flux in the end windings. The 540° transposition, attributed to Ringland and Rosenberg (1959) is often applied because it filters out most of the circulating currents in a bar. Other more complex Roebel transposition arrangements that more extensively filter out circulating currents are possible but are rarely used because of manufacturing complexity. Bapat (1973) and Neidhoeffer (1990) outline general surveys about special transpositions.

7.6 INSULATION SYSTEMS

Electrical insulation is used to isolate field conductors from each other and ground, and in the armature winding to isolate strands and turns from each other and the whole winding from ground. Proper application of electrical insulation constitutes much of the art of ac machine design, particularly in the larger generator sizes.

7.6.1 Materials

International standards have established various classes of insulation systems based primarily on the maximum steady-state operating temperature and have established voltage proof tests to demonstrate the dielectric capability of insulation systems.

Of the several thermal classes of insulation systems, three are most applicable to ac generators. These are Classes 130, 155, and 180. Class 105 insulation materials are no longer used in modern

ac generators. In the most recent revisions of IEEE C50-12 and C50-13, and IEC 60034-1 and 60034-3 standards for ac generators, the numerical classifications 130, 155, and 180 have been substituted for the previously used alphabetical classifications B, F, and H, respectively.

Class 130 systems comprise inorganic materials such as mica and glass fibers, organic materials such as synthetic films, and suitable binders. Until recently, Class 130 systems have been identified as Class B systems.

Class 155 systems comprise generally similar materials with binders capable of higher temperatures. Until recently, Class 155 systems have been identified as Class F systems.

Class 180 systems include silicone elastomers as well as mica, glass fibers, and higher-temperature binders. Until recently, Class 180 systems have been identified as Class H systems.

Synthetic chemistry has presented a continued flow of materials suitable for electrical insulation, and any of the above-mentioned insulation systems may be supplemented by new materials.

7.6.2 Temperature Measurements

Several methods of observing winding temperatures are used. Note that it is ordinarily not practical to actually measure the “hot spot” temperature directly, so that an allowance is normally given, based on the method of temperature measurement used.

Thermometer method. A thermometer (mercury filled, or other suitable temperature measuring device) may be applied to what is expected to be the hottest part accessible. Of the several methods described, this one gives readings furthest from the maximum winding temperature and therefore has the highest hotspot allowance.

Resistance method. The resistance of electrical conductors is a function of temperature. Thus, if the resistance of the winding can be measured and its resistance at a reference temperature is known, the average temperature of the winding may be calculated

$$T_2 = K + \frac{R_2}{R_1} \cdot (1 + T_1) \quad (7-48)$$

where R_1 is the resistance at temperature T_1 and R_2 is the resistance at temperature T_2 . The constant K is 234.5°C for copper, 242°C for silver-alloyed copper used for hollow conductors, and 225°C for electrical conductivity aluminum.

Discharge coolant method. For directly cooled armature windings in the largest generators, the observable temperature is the coolant being discharged from the armature coils.

Embedded detector method. Thermocouples or resistive thermal detectors are built into the machine. In the most common application these are placed between the coil sides in a two-layer armature winding near the axial center or warmest region of the core.

Applied thermocouple method. Thermocouples are applied directly to the conductors, with little or no insulation. This method is used only for experimental testing to, for example, determine hot-spot allowances. It is not used for operational measurements.

7.6.3 Temperature Ratings

Temperature ratings of ac generator windings are based on measurements of winding temperatures and the thermal class of insulation used. These measurements are specified in IEEE C50-12 and C50-13, and IEC 60034-1. Generally, machines with smaller ratings employ the resistance method and larger machines employ embedded detectors or discharge coolant measurement methods.

7.6.4 Armature-Winding Insulation

Armature voltages range from about 220 V to about 27 kV. With such a wide range, different techniques are employed. In the armature, insulation is for strands, turns, and ground wall.

Strand insulation is required to prevent circulating currents within a conductor bar. The voltage levels are not high so mechanical integrity is the important feature of strand insulation. This is usually a layer of served fabric or film coating.

Turn insulation is used in multiturn coils, generally applicable only in small-size generators. This insulation is required to withstand turn-turn voltage, although in some cases large transient spikes of voltage may be incident on the winding.

Ground wall insulation must withstand full voltage to ground. Typically, the whole of an armature winding is insulated for full voltage, even though some of the coils, located near the neutral end of the winding, see lesser voltage.

In high-voltage armatures (above ~5 kV), some measures must be taken to control the effects of corona and partial discharge. In the slot portion of the coil, it is necessary to prevent discharges due to capacitive coupling through the insulation, from the surface of the insulation to the grounded stator core. These discharges are prevented by coating the outer surface of the insulated conductor with a conductive (sometimes called semiconducting) coating (paint or tape). To prevent discharges along the surface of the conductors in the end windings, those sections are sometimes coated with very weakly conducting coatings that are called grading coatings (paint or tape).

It is important to prevent electrical discharges in the vicinity of the winding because such discharges through air and in the presence of any water vapor will produce nitrous and nitric acid and ozone, substances corrosive to the materials of the winding.

7.6.5 Field-Winding Insulation

Field windings operate at much lower voltages (usually less than ~800 V). Some transient conditions, such as interruption of field current, can lead to much higher voltages.

Field windings are subject to the centrifugal forces due to rotation, and this presents special challenges. Dimensional stability is required of the field winding to prevent dynamic rotor imbalance. It is also necessary, in larger machines, to allow the field winding to expand thermally with respect to the rotor steel. The resulting “creepage” surfaces must allow slip in the axial direction but not movement in the other directions.

7.6.6 Insulation Maintenance

Failure of the insulation system of a generator produces a prompt outage of the generator. This produces ample reason to maintain the insulation system in good order. Insulation maintenance involves measures to reduce or eliminate sources of abnormal aging and damage to insulation, inspection to determine if deterioration has taken place, and testing to assess the state of the insulation system.

Service Conditions. Some operational conditions that produce accelerated insulation deterioration and ways of controlling them are described as follows:

Excessive temperature may be caused by blockage of ventilation paths or cooling tubes or by overload. Measurement of winding temperature is used to detect overtemperature conditions to allow the cause to be corrected.

Excessive voltage may be caused by control errors, but is usually the result of switching operations or lightning. This is usually a matter for correct system design to prevent such overvoltages.

Contamination can affect windings in one of the three ways. Some contaminants may attack insulation system, reducing its dielectric strength or affecting its mechanical properties. Some contaminants may thermally insulate parts, causing excessive temperatures. On the other hand, some contaminants such as conducting particles may lead to abnormal potential distribution and

excessive voltage stresses. Control of contamination consists of preventing substances from entering the generator (if possible) and of inspecting periodically for signs of contamination or related damage.

Physical damage to insulation can occur for a variety of reasons, including vibration, overspeed, short-circuit forces or improper synchronization, and even damage by foreign objects. Generally, prevention and inspection are used to control such damage.

Corona, an electrical discharge around the surface of stator insulation, may be caused by contamination or by some inherent weakness in the insulation system itself.

Inspection. Visual inspection supplemented with simple physical tests may be carried out to diagnose incipient problems that might lead to eventual insulation failure. Some symptoms are described as follows:

Swelling or shrinking is evident from visual inspection, probing, and tapping on the insulation. Swelling is accompanied by reduction in physical integrity and sometimes by separation of insulation from the underlying conductor. Shrinkage leads to looseness in the slot.

Cracking results from abnormal mechanical stress or poor winding support. *Girth cracking* is displacement of insulation near the core ends of relatively large machines, caused by thermal cycling.

Substances noted on the winding can include contaminants such as oil, dust, and water and also deposits produced by corona, which may be white, gray, or red and may appear in regions of high electrical stress.

Slot wedges and fillers may become loose in service. This will lead to deterioration if not corrected, so any inspection of a generator should include checking of all the stator slot wedges.

Tests of Insulation Systems. Before commissioning a new generator and as part of generator maintenance programs, tests of insulation systems are carried out. There is a wealth of literature on this topic cited in the references. What appears here is only a first-order synopsis.

Testing of insulation systems in ac generators is used to uncover existing weaknesses or faults and to produce an indication of expected service reliability.

Some tests commonly employed are described as follows:

Insulation resistance is a straightforward test used to indicate the existence of contamination or moisture absorption. It seldom indicates the existence of an incipient fault. It is difficult to assign specific acceptable values for the results of insulation resistance tests, but it is possible to 'trend' the results of such tests.

Dielectric absorption tests are similar to a dc resistance test. A voltage in the range of 500 V to 5 kV is placed across the insulation and current is measured as a function of time. The *apparent* resistance is the ratio of voltage to current and is a function of time. The *polarization index* is the ratio of the value of this apparent resistance after 10 to the value after 1 min. The polarization index may be used for trending. Generally, for Class 130 and Class 155 insulation, a polarization index of about 2 or greater is an indication of a healthy winding, while a value of 1 or less is an indicator of potential trouble. Further description of resistance and dielectric absorption tests is contained in IEEE Standard 43.

Overvoltage tests are proof tests. Failure of an overvoltage test (called also *high potential* or *hi-pot*) is destructive. Such tests are carried out because failure of an insulation system under test conditions is much less damaging than failure in service. Overvoltage tests may be carried out with either ac or dc voltage, and employ voltage levels that are selected for the particular test. New windings (whether in a new generator or in a newly rewound generator) are typically tested to higher levels relative to their operating voltage, than are older windings that have been in service for a significant portion of their expected life. Typical values of high potential for testing new windings are twice operating line to line voltage plus 1000 V. Typical values of high potential for testing mature windings are between 125% and 150% of operating line to line voltage.

Direct current test voltage is related to the peak of the equivalent ac voltage. Details and test procedures are included in IEEE Standards 4 and 95.

Slot discharge may be detected in operation by using a *corona probe*, an antenna located inside the machine (Kurt et. al. 1984).

Rotor winding impedance tests can be used to detect failure of field-winding resistance. An alternating voltage is placed across the field winding, and individual coil voltages are measured. If the measured voltages are not the same, there is an indication of short-circuited turns.

Insulation power factor tests are generally used only on high-voltage machinery (above ~6 kV). Normally, the power factor, measured when applying voltage to a winding and measuring current, is quite low. Power factor measured as a function of applied voltage may be used for trending, and an increase in power factor with voltage is an indication of developing voids in the insulation.

Controlled overvoltage or dc leakage tests consist of measuring leakage current versus time. These tests are detailed in IEEE Standard 95.

7.6.7 Stator-Core Insulation

The stator core is made up of thin sheets of electrical steel that are coated by thin films of organic or inorganic insulation.

7.7 MECHANICAL CONSTRUCTION

Generators consist of a rotor, a stator and those mechanical parts required to hold the machine together and assure proper alignment, cooling, and other aspects of operation. Design criteria for the mechanical aspects of machine construction are based not only on anticipated steady state operation but also on abnormal aspects of operation such as overspeed and short circuits.

Essential variations in machine construction are salient pole versus round rotor and horizontal versus vertical shaft. In virtually all modern alternators the field is the rotating element and the armature is the stationary element. In salient-pole construction the field windings are wound around pole pieces. Such construction is used for machines with at least 6 poles, corresponding to shaft speeds of 1200 r/min or less in the 60-Hz world, or 1000 r/min in the 50-Hz world. Round-rotor construction, in which field windings are inserted in axial slots in a cylindrical rotor body, is used in essentially all 2-pole machines and most 4-pole machines because attaching salient poles to a rotor shaft becomes problematical at the higher shaft speeds associated with such machines.

The prime mover determines if the shaft is horizontal or vertical. Most generators driven by steam turbines, gas turbines, or reciprocating engines have horizontal shafts. Larger, low-speed hydraulic turbines have vertical shafts, while smaller, higher-speed turbines can have shafts that are vertical, horizontal, or even inclined. Magnetic circuits, stator, and armature windings of all machines are similar, only structural details differ.

7.7.1 Stator Construction

Armature cores are built up of thin laminations, produced as either segments or complete rings, depending on the size of the generator. Successive layers or groups of layers of the segmented laminations are staggered to minimize the effect of the joints in the magnetic circuit. The core is clamped between pressure plates and fingers to support it with sufficient pressure to prevent undue vibration of the laminations. Especially in long cores, the clamping arrangement may include some provision to compensate for compacting of the core after initial assembly.

The armature windings are fitted tightly in the slots and secured radially by wedges driven into suitable notches at the air gap end of the slots. It is necessary that the stator coil ends be able to resist the abnormal forces associated with short circuits. A supporting structure may be employed for this

purpose. There are many variations of support design; most of them provide filler blocks between the coil sides, strategically located to transmit the circumferential forces from coil to coil, and additional structure to counteract the radial forces.

Coil supports ordinarily are designed to suit the need of a particular machine. Large 2-pole machines require a quite elaborate structure; the combination of large short-circuit currents and coil ends inherently flexible because of their long length makes these machines particularly susceptible to coil-end movement. Low-speed machines with stiffer coil ends require less support; in the smallest ratings the coils may be capable of withstanding the short-circuit sources without any additional support.

Stator frames, sometimes called casings, are commonly fabricated from structural steel, designed to support the core in alignment with the rotor and to suit the ventilating scheme used. In large machines with 2-pole or sometimes 4-pole construction, the stator core is mounted on springs to isolate core vibration from the machine frame.

7.7.2 Rotor Construction

The pole pieces of salient-pole alternators may be built up of steel laminations, both as manufacturing convenience and a means of limiting the loss in their air gap surfaces due to pulsations in air gap flux. The field coils, wound directly on the poles or preformed and then mounted on the poles, are suitably insulated from the poles for the voltages associated with normal and transient operation. The pole-and-coil assembly is bolted, dovetailed, or otherwise attached to the rotor body. It is the limitation of this attachment which usually dictates when round-rotor construction must be used rather than salient-pole construction.

The rotor body for a salient-pole machine may be a solid forging or assembly of heavy steel plates, for high-speed designs, or a spider-and-rim assembly for low-speed designs. The shaft may be integral with the body, as in the case of a forging, or may be bolted to or inserted into the body.

When the spider-and-rim construction is used, the entire assembly may be an integral weldment or casting, or the rim may be separate from the spider, as in the case of large waterwheel-driven generators. A common construction for this latter case is a rim built up of thin steel laminations, assembled around a cast or fabricated spider, bolted together between steel end plates and keyed to the spider.

The rotor of a round-rotor machine is cylindrical in shape with axial slots provided in its body for the field coils. The body is usually a steel forging with integral shaft ends. In special applications, other constructions may be used, with this same general configuration. The field coils are wound in axial slots in the rotor body, held in place by heavy slot wedges and by retaining rings over the coil ends.

Rotors are designed for operation at overspeeds, which depend on the characteristics of the prime mover. The overspeed limit (the speed above which the unit is no longer capable of safe operation) may be as low as 20% for a steam-turbine-driven unit or as high as 125% for some adjustable-blade, axial-flow hydraulic turbine-driven units.

7.7.3 Critical Speeds

The shaft system of the entire unit (generator plus prime mover) must be designed with regard to critical speeds. Both lateral and torsional critical speeds are considered. *Lateral critical speed* is the speed corresponding to the natural frequency of the shaft system in response to lateral or transverse forces such as residual unbalance forces. *Torsional critical speed* relates to the response of the shaft system to torsional forces. The lateral critical speed is associated with each mode of lateral vibration, the first critical speed corresponding to the lowest-frequency mode. Critical speeds are affected by shaft support, including foundation (particularly lateral critical speeds), and by internal and external damping.

It is preferable that the operating speed be at least 10% away from the nearest critical speed. Low-speed rotors ordinarily operate below the first critical speed. High-speed rotors, especially 2- and 4-pole turbogenerator rotors, usually operate above the first critical speed and sometimes above the

second or even third critical speed. Multiplane balances are required for such rotors, and carefully planned speed profiles on start-up are required to avoid excessive stresses.

Torsional critical speeds are excited by external forces such as sudden load change, or a short circuit or other system disturbance, or cyclic variations in prime mover torque, such as from an internal combustion engine. Impulses from the buckets of a hydraulic turbine or from the gear teeth in a unit driven through the gear may also excite torsional vibrations.

It is possible that some components of a shaft system may have resonant frequencies, which are close to those that might be excited in operation. For example, long, last-stage turbine buckets might have a resonance at nearly twice the operating frequency, and that frequency is likely to be excited by negative-sequence currents. Care is required in selecting all components of the shaft system.

7.7.4 Bearings

Although, antifriction bearings are occasionally used on alternators of smaller ratings, the great majority are furnished with oil-lubricated babbitted bearings. For horizontal shafts at small ratings ring-oiled bearings are used, but at higher ratings recirculation of externally cooled oil is used.

Two principal types of thrust bearings are used on vertical alternators: the pivoted-shoe type and the spring type. The adjustable *pivoted-shoe* type, introduced in the United States by Albert Kingsbury, consists of a flat rotating collar or runner of steel or fine-grained cast iron resting on a stationary member consisting of several babbitted segmental shoes pivoted near their center on adjusting screws, which, by changing the elevation of the shoes, can provide equal loading on each. The screws also permit small adjustments in rotor elevation to correct generator and turbine clearances.

The bearings are immersed in oil. In operation, a thin, wedge-shaped film of oil is formed between the runner and the shoe. The oil is continuously circulated by the rotation of the runner and is cooled by either radiation or water cooling, usually within the oil bath but occasionally by an external system. Some of the larger bearings are cooled by means of water circulate through tubes embedded below the babbitt surface.

The *spring*-type bearing is inherently self-equalizing; that is, each shoe carries very nearly the same amount of load. A variation of the pivoted-shoe bearing, in which the shoes are supported on a system of interconnected levers, provides the same self-equalizing feature.

The *spherical bearing* is another variation of the pivoted-shoe thrust bearing, in which the runner is part of a sphere and the shoes of corresponding shape. This type of bearing restrains lateral movement of the shaft, serving the dual function of thrust and guide bearing.

Horizontal-shaft alternators occasionally require thrust bearing, as, for example, a single-impeller reaction turbine having unbalanced hydraulic thrust which must be restrained by the bearing. Thrust bearing designs for this application are generally of the pivoted-shoe type, either adjustable or equalizing.

Some thrust bearings, particularly of the adjustable pivoted-shoe type, may be provided with load cells for measuring and equalizing the thrust on the shoes. These may be of the hydraulic or strain-gage type, the latter is more common in modern applications. In addition to providing a check on the adjustment of the shoe loadings, these devices provide information about the hydraulic thrust characteristics of the turbine.

Guide bearings for vertical alternators are oil-lubricated babbitted rings. These are frequently segmented to facilitate assembly and may be composed of individual shoes which are radially adjustable. Guide bearings usually are partly immersed in an oil bath with oil circulated by the pumping action of sloping grooves in the babbitt surface. Occasionally, a separate lubrication system is provided which introduces oil at the top clearance of the bearing, collects it at the bottom, and recirculates it. It is common practice to place a guide bearing closely above the thrust bearing in the same oil pot. In some instances a guide bearing is on the outer periphery of the thrust runner.

Bearing Arrangements. Vertical alternators are classified by their bearing arrangement. In *suspended unit* the thrust bearing is located above the rotor and is provided with two guide bearings,

one above the rotor and one below. The upper guide bearing is frequently placed just above and in the same oil pot as the thrust bearing. In “umbrella” unit, the thrust bearing is located below the rotor and one guide bearing also below the rotor, usually in the same oil pot and just above the thrust bearing. When umbrella arrangements are used, careful consideration must be given to the stability of the unit with respect to overturning moments. Large diameter, slow-speed units, in which the ratio of rotor diameter to the height of rotor center of gravity above the thrust surface is relatively large, lend themselves to umbrella construction. A principal advantage of umbrella construction is a substantial reduction in required powerhouse headroom, since the relatively high bearing support structure is below the rotor in the turbine pit. Furthermore, this structure itself usually spans a shorter distance when placed below the rotor and is not so high because of this, and shaft length may be reduced. A modified umbrella arrangement, having a guide bearing above the rotor, may be used when mechanical stability precludes classic umbrella construction. This retains some of the advantage of reduction in headroom requirement. The thrust bearing may be supported from the turbine head cover to achieve a more compact arrangement.

High-Pressure Lubrication. Horizontal journal bearings and thrust bearings are often provided with high-pressure oil (“jacking oil”) to reduce starting torque and minimize bearing wear on start-up. Oil at pressures on the order of 10 MPa is introduced at the bottom of the journal bearing or at the center of each shoe or segment of a thrust bearing to lift the rotor and introduce an oil film in the bearing clearance before the shaft rotates.

Steam turbine generator units frequently are operated at very low speeds when they are disconnected from the system to prevent the shaft system from sagging while cooling or while at stand-still for extended periods. This “turning gear” operation may be at 5 to about 50 r/min much below the speed at which the bearing would maintain an oil film. Jacking oil is usually used during this operation.

7.8 LOSSES AND EFFICIENCY

Efficiency of a generator is defined as

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \cong 1 - \frac{P_{\text{dissipation}}}{P_{\text{out}}} \quad (7-49)$$

Windage and friction includes loss from the bearings, shearing of the air or hydrogen at the rotor surface, mechanical work done on the air or hydrogen that flows through the rotor, and power expended by the cooling fans. This loss is generally not a function of operating point, but it does vary with the pressure of the cooling gas inside the generator. Provided that the cooling gas pressure is kept constant, this loss is usually considered to be independent of load.

Core loss is caused by hysteresis and eddy currents in the core laminations. It also includes losses induced in structural parts of the machine that are exposed to stray alternating magnetic flux at no-load conditions. Core loss is a function only of terminal voltage, and it is usually considered to be independent of load.

Field loss is ohmic loss caused by field current flowing in the field winding. This loss depends on both the field current and the temperature of the field winding. It thus varies with load.

Armature loss is ohmic loss caused by armature current flowing in the armature winding. This loss is defined by the square of the armature current multiplied by the dc resistance of the armature winding, corrected for temperature. This loss varies with load.

Stray load loss explains sources of loss not adequately covered by the other categories. It includes eddy current loss in the armature and losses in structural elements exposed to magnetic fields arising from armature current and to those parts of the rotor surface affected by armature leakage

fields. Stray loss is generally proportional to the square of armature current and may, with only small error, be expressed as a fraction of armature transport loss.

7.9 TESTING OF AC GENERATORS

Tests are performed on generators to establish conformance with projected performance and dynamic performance parameters. Details of such tests are contained in IEEE Standard 115, IEC 60034-2 and IEC 60034-4 standards.

7.9.1 Resistance

Field and armature resistances are typically small, so measurements should be made using a 4-wire technique. It is important that resistance be measured at a known temperature so that correction can be made to actual operating temperature.

7.9.2 Open-Circuit Saturation Curve

The generator is driven by a motor to rated speed and excitation varied to produce terminal voltage over a range, typically from perhaps 30% to 120% that of rated. Some caution is required here, particularly for large machines in which excessive flux can damage the core. Open-circuit losses may be established by this test if the drive motor is well characterized and input power is measured.

7.9.3 Short-Circuit Saturation Curve

This test is similar to the open-circuit test, except the armature terminals are short-circuited and excitation varied to produce armature current over some convenient range. Windage and friction losses may be inferred from power input at zero excitation. Stray load loss may be estimated as the difference between input power at rated armature current and the sum of friction and windage and armature I^2R .

7.9.4 Zero Power Factor Saturation Curve

For a relatively small generator, the zero power factor saturation curve can be determined by running the machine with its shaft unloaded, driven by a second generator.

By adjusting the excitation on the ac generator under test and excitation on the second generator, it is possible to measure the zero power factor saturation curve.

Rather extensive discussion of this method is described in IEEE 115. For large generators for which this “back-to-back” method is not practical, the zero power factor curve is usually determined by numerical methods. Often those methods employ finite elements.

7.9.5 Deceleration

Deceleration may be used for determining losses if the inertia of the machine is known. Since, if the shaft of a machine is unloaded, power dissipated is

$$P_w = \omega_m J \frac{d\omega_m}{dt} = \frac{d}{dt} \left\{ \frac{1}{2} J \omega_m^2 \right\} \quad (7-50)$$

where ω_m is mechanical speed, deceleration through synchronous speed can give a good measure of dissipation. The test may be run with the machine operating either at open-circuit or short-circuit conditions, or at zero excitation. It is usually run from a slight overspeed. This test can be used to determine an unknown inertia from known losses and observed deceleration.

7.9.6 Heat Runs

These are tests performed by operating the generator at some condition until the temperature stabilizes. Heat runs at open-circuit, short-circuit, and zero power factor may be combined to estimate temperature rise in actual operation. In large machines, good estimates of dissipation may be made by measuring the temperature rise of coolant (e.g., water). This is an alternative or supplement to measuring input power to the drive motor or machine deceleration. ω_m

7.10 COOLING

Dissipation in generators appears as heat which must be removed. This heat appears in the armature conductors, field-winding conductors, stator core, rotor surface, and other structural elements of the machine. Cooling of armature and field conductors may be direct or indirect; the difference is direct contact of the cooling medium with the conductor or contact through electrical insulation.

7.10.1 Cooling Media

Alternating-current generators may be cooled by air, hydrogen, water, or (very infrequently) oil. In large machines, no matter what the cooling medium, heat is transferred to water in heat exchangers that are located within the machine case.

Smaller machines are cooled by air. Recently, there has been a trend toward air-cooling larger machines. The upper limit in size for air-cooled machines is, as of this writing, about 350 MVA, and may increase further. The advantage of air cooling is simplicity. The disadvantage is machine size.

Hydrogen has had wide application in cooling of larger generators. It has a high specific heat and thermal conductivity and low density, so it provides better heat transfer with lower windage losses than does air. Hydrogen also does not support oxidation, with some advantage to insulation systems. Cooling a generator with hydrogen requires additional systems to maintain hydrogen purity and to remove hydrogen from lubricating oil and shaft seals. Since the “explosive” range of hydrogen/oxygen mixtures is about 5% to 75% hydrogen, if the purity of hydrogen is kept above about 95%, the cooling medium will be nonexplosive.

Water is used in armature winding cooling in very large machines.

7.10.2 Ventilation Paths

Fans used in electric machines may be of either radial flow or axial flow, and a wide variety of cooling paths are used. Figures 7-22 and 7-23 show two possible schemes.

7.10.3 Stator-Core Ventilation

The stator core is usually gas (air or hydrogen)-cooled. Axial passages through the core may be formed by punching holes in the laminations. Radial passages are formed by spacers that hold the core packets apart. Radial passages might be about 1 cm in axial length with spacing of about 5 cm.

In some cases, as shown in Fig. 7-22, axial and radial cooling passages are mixed in one machine. In some cases, the ventilating gas passes first radially inward and then radially outward.

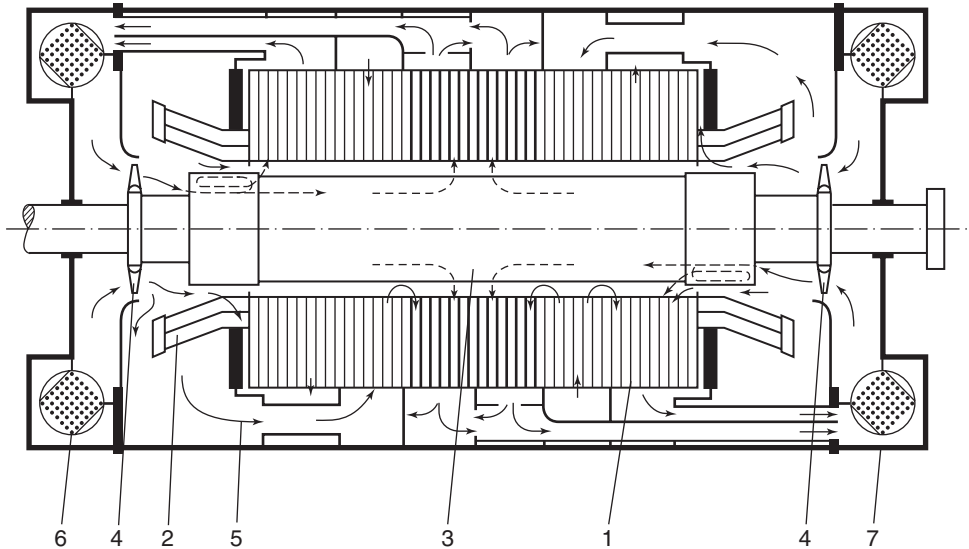


FIGURE 7-22 Cooling system, gas only. (1) stator core; (2) indirect-cooled stator winding; (3) rotor body; (4) axial-flow fans; (5) gas flow; (6) hydrogen cooler; (7) stator housing. (ABB.)

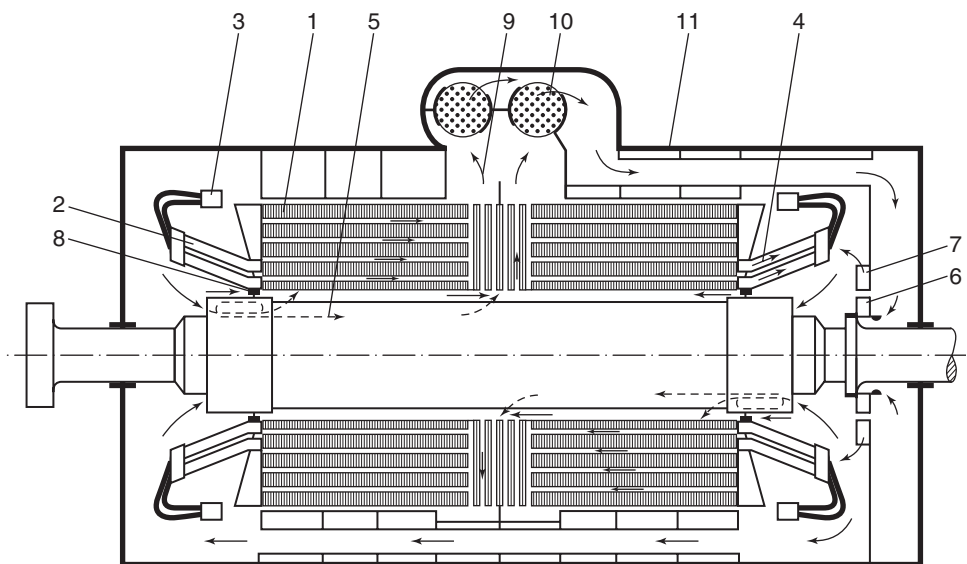


FIGURE 7-23 Cooling system, combination of gas and water. (1) stator core; (2) water-cooled stator winding; (3) water manifold; (4) water flow; (5) rotor body; (6) radial-flow fan; (7) diffuser; (8) air gap baffle; (9) gas flow; (10) hydrogen cooler; (11) stator housing. (ABB.)

7.10.4 Rotor Ventilation

As with the stator core, rotor cooling takes on a variety of forms. In some cases cooling gas passes axially from the ends of the rotor and then exits through holes in the rotor surface into the air gap, and then passes through the stator core. In other cases, gas passes radially inward from the air gap, diagonally through the rotor, and then radially outward to the air gap. This scheme can be coordinated with cooling of the stator core.

7.10.5 Direct and Indirect Cooling

Direct cooling, the norm for rotor windings and widely used in stator windings, exposes the cooling medium directly to the conductors. Figure 7-24 shows hydrogen and water directly cooled conductors for both stator and rotor.

In a directly gas-cooled stator, relatively large passages are built into the conductor bar. The conductor strands are transposed around the gas passages. There is strand insulation between the conductor strands and gas passage (which is often made of stainless steel), but the gas is within the ground wall. In a directly gas-cooled rotor the gas flow may be radial, axial, or diagonal, or some combination of all three.

In a directly water-cooled stator winding, the water flow may be in direct contact with the conductors. In some cases some or all of the conducting strands are made of hollow copper tubing. In others, stainless-steel tubes are used. Typically, water flows through the machine only one or two axial passes before being returned to the cooler. If water cooling is used, then

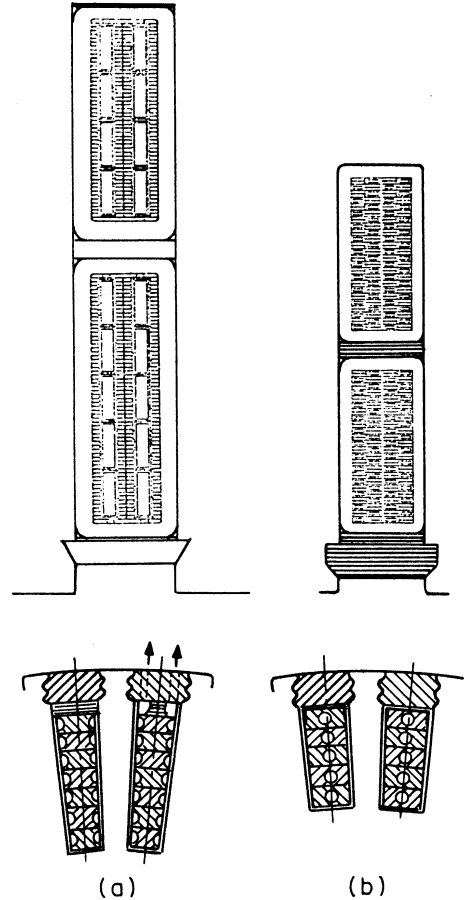


FIGURE 7-24 Directly cooled conductors; (a) hydrogen; (b) water.

1. The water is maintained at very high purity so that it has low conductivity.
2. Water is carried to the armature conductors through specially made hoses, since the conductor bars are at high potential and the water header is at ground.
3. Generally, hydrogen pressure in the machine is maintained above water pressure so that any leak will be of hydrogen into the water system, rather than water into the electrical insulation.

Water-cooled field windings are relatively rare, although many have been in highly reliable service for decades in some of the world's most powerful nuclear turbine generators.

7.11 DYNAMIC MODELS

In applying an ac generator to power systems, it is important to understand the dynamic performance of the machine. This section describes one way of estimating the dynamic performance of a

generator. There is much literature on this topic, however, and what is done here will only skim the surface of a very deep topic.

Typical among the dynamic issues are levels of fault current, transient stability limits, responsiveness to excitation control, and damping of transient swings.

7.11.1 Per Unit System

Voltages, currents, and impedances are often expressed as *per unit* values, that is, a base for each quantity is assumed and every ordinary variable is compared with that base. Thus, when a machine is operating at its rated condition, both voltage and current magnitude could be said to be “one per unit.” Multiplying voltage and current yields power, while dividing voltage by current yields impedance magnitude, so these can be expressed in per unit terms as well. The general form of the per unit (pu) is shown in Eq. 7-51.

$$pu = \frac{\text{actual}}{\text{base}} \quad (7-51)$$

Generally, the base apparent power or total power (S_{base}) and the base voltage (V_{base}) are specified; all other base values are determined from these two.

The use of per unit quantities has a number of advantages in analysis of electric machines. Not the least of these is that the use of the per unit index eliminates the need to refer to peak or rms, line neutral or line ground. In this development, all voltages, currents, fluxes, powers, and torques will be expressed in per unit. Time will not, however, be normalized, so rotational speed is measured in radians per second and time constants, in seconds.

7.11.2 Represented Circuits

Typical electrical models of electric machines represent the relationship between voltage and current in the various windings of the machine. Thus, the three phase windings and the field winding are represented. Important dynamics, however, arise from currents in elements of the rotor surface, the rotor body or amortisseur or damper bars, or some combination of all of these factors. These are typically represented by equivalent windings, too. For the purpose of this discussion, only one additional winding (referred to here as the “damper”) will be included for each axis of the rotor.

The analysis begins with normalized variables referred to as the *direct* and *quadrature axes* of the machine. The per unit fluxes are

$$\begin{bmatrix} \psi_d \\ \psi_{kd} \\ \psi_f \end{bmatrix} = \begin{bmatrix} x_d & x_{ad} & x_{ad} \\ x_{ad} & x_{kd} & x_{fd} \\ x_{ad} & x_{fd} & x_f \end{bmatrix} \begin{bmatrix} i_d \\ i_{kd} \\ i_f \end{bmatrix} \quad (7-52)$$

$$\begin{bmatrix} \psi_d \\ \psi_{kd} \end{bmatrix} = \begin{bmatrix} x_q & x_{ad} \\ x_{aq} & x_{kd} \end{bmatrix} \begin{bmatrix} i_q \\ i_{kd} \end{bmatrix} \quad (7-53)$$

where the variables ψ represent per unit fluxes and i represents per unit currents. Subscripts d and q represent the direct and quadrature axes, respectively, while the subscripts a , k , and f represent the armature, damper, and field. There are only two armature variables here, where, strictly speaking, a third would be required. Ordinarily, the “zero” axis variable can be ignored as generators are usually connected so that no current can flow in that winding.

7.11.3 Equivalent Circuits

The equivalent circuits shown in Fig. 7-25 represent the same flux-current relationship as do Eqs. (7-52) and (7-53), with winding resistances added if

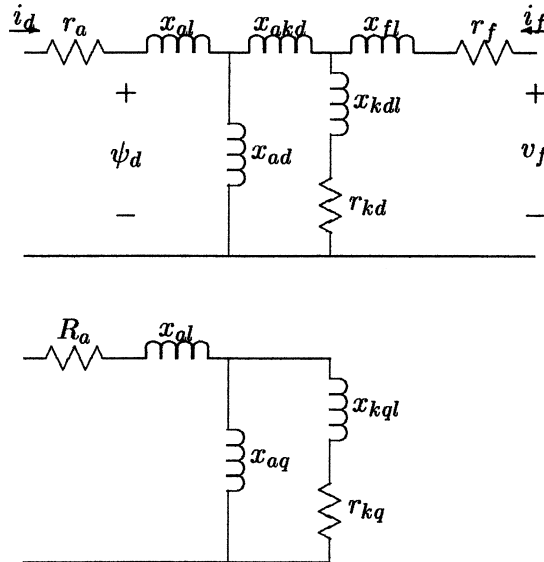


FIGURE 7-25 Direct and quadrature-axis equivalent circuits.

$$x_d = x_{al} + x_{ad} \quad (7-54)$$

$$x_{fd} = x_{ad} + x_{akd} \quad (7-55)$$

$$x_{kd} = x_{fd} + x_{kdl} \quad (7-56)$$

$$x_f = x_{fd} + x_{fl} \quad (7-57)$$

$$x_q = x_{al} + x_{aq} \quad (7-58)$$

$$x_{kq} = x_{kql} + x_{aq} \quad (7-59)$$

The interesting dynamics of the rotor can be now described by these two equivalent circuits.

7.11.4 Parameters

The various reactance and resistance parameters of the equivalent circuits of Fig. 7-25 may be calculated from first principles or may be measured by several different techniques. For example, IEEE Standard 115 describes a frequency response technique for measuring these parameters. Note that the parameter x_{al} appears in both direct- and quadrature axes. For this reason an apparently superfluous variable, x_{akd} , is used on the direct axis to allow an extra degree of freedom for an adequate “fit” between measurements and the equivalent circuit.

The equivalent circuits of Fig. 7-25 are only approximations to the actual performance of ac generators. In some cases it will be necessary to use higher-order models. Generally these are represented by multiples of the damper winding with different magnitudes and time constants. These are beyond the scope of this discussion.

7.11.5 Voltages

Voltages are produced by time variations of fluxes and by rotation of the machine. Translated into per unit measurement the voltages are

$$v_d = \frac{1}{\omega_0} \frac{d\psi_d}{dt} - \frac{\omega}{\omega_0} \psi_q + r_a i_d \quad (7-60)$$

$$v_q = \frac{\omega}{\omega_0} \psi_d + \frac{1}{\omega_0} \frac{d\psi_q}{dt} + r_a i_q \quad (7-61)$$

$$v_f = \frac{1}{\omega_0} \frac{d\omega_f}{dt} + r_f i_f \quad (7-62)$$

$$v_{kd} = \frac{1}{\omega_0} \frac{d\psi_{kd}}{dt} + r_{kd} i_{kd} \quad (7-63)$$

$$v_{kq} = \frac{1}{\omega_0} \frac{d\psi_{kq}}{dt} + r_{kq} i_{kq} \quad (7-64)$$

$$v_0 = \frac{1}{\omega_0} \frac{d\psi_0}{dt} + r_a i_0 \quad (7-65)$$

7.11.6 Simulation Model

These expressions may be turned into a concise simulation model, suitable for use in modern computing apparatus for estimating performance of an ac generator. This is simply done by isolating the first-order time derivatives.

The state variables are the two stator fluxes ψ_d , ψ_q , two “damper” fluxes ψ_{kd} , ψ_{kq} , field ψ_f , and rotor speed ω and torque angle δ . The most straightforward way of stating the model employs currents as auxiliary variables

$$\begin{bmatrix} i_d \\ i_{kd} \\ i_f \end{bmatrix} = \begin{bmatrix} x_d & x_{ad} & x_{ad} \\ x_{ad} & x_{kd} & x_{fd} \\ x_{ad} & x_{fd} & x_f \end{bmatrix}^{-1} \begin{bmatrix} \psi_d \\ \psi_{kd} \\ \psi_f \end{bmatrix} \quad (7-66)$$

$$\begin{bmatrix} i_d \\ i_{kd} \end{bmatrix} = \begin{bmatrix} x_q & x_{ad} \\ x_{aq} & x_{kd} \end{bmatrix}^{-1} \begin{bmatrix} \psi_q \\ \psi_{kd} \end{bmatrix} \quad (7-67)$$

Then the state equations are

$$\frac{d\psi_d}{dt} = \omega_0 v_d + \omega \psi_q - \omega_0 r_a i_d \quad (7-68)$$

$$\frac{d\psi_q}{dt} = \omega_0 v_q - \omega \psi_d - \omega_0 r_a i_q \quad (7-69)$$

$$\frac{d\psi_{kd}}{dt} = -\omega_0 r_{kd} i_{kd} \quad (7-70)$$

$$\frac{d\psi_{kq}}{dt} = -\omega_0 r_{kq} i_{kq} \quad (7-71)$$

$$\frac{d\psi_f}{dt} = -\omega_0 r_f i_f \quad (7-72)$$

$$\frac{d\omega}{dt} = \frac{\omega_0}{2H} (T_e + T_m) \quad (7-73)$$

$$\frac{d\delta}{dt} = \omega - \omega_0 \quad (7-74)$$

and

$$T_e = \psi_d i_q - \psi_q i_d \quad (7-75)$$

For a practical simulation, v_d , v_q , and mechanical torque T_m must be specified.

7.11.7 Approximate Analysis

It should be clear from examining the equivalent circuits of Fig. 7-25 that the behavior of the machine, meaning its flux/current relationship, is a function of the speed of any given disturbance. This leads to approximate analyses of ac generators, which recognize the frequency dependence of the rotor elements.

Synchronous reactances x_d and x_q are applicable when the rotor is moving in synchronism with the magnetomotive force (mmf) produced by the armature currents, or when the deviation in speed is very small.

Transient reactance x'_d is applicable when armature mmf is changing with time, as in electro-mechanical transients or “swings.” This effective reactance is reduced by the tendency of (nearly) short-circuited field winding to trap or hold flux nearly constant for periods comparable to or shorter than its time constant. This reactance is

$$x'_d \approx x_{al} + x_{ad} \parallel (x_{fd} + x_{fl}) \quad (7-76)$$

In some types of generators there may be an identifiable transient reactance on the quadrature axis, less than the quadrature-axis synchronous reactance, but in others the applicable reactance to use for the quadrature axis in transient events is just x_q .

For transient events that occur very rapidly, such as switching events and terminal short circuits, the effective reactances are the *subtransient* reactances. These result from the tendency of the amortisseurs (or even rotor iron) to support or trap flux. They are

$$x''_d = x_{al} + x_{ad} \parallel (x_{akd} + x_{kdl} \parallel x_{fl}) \quad x''_q = x_{al} + x_{aq} \parallel x_{kql} \quad (7-77)$$

The foregoing reactances are applicable when the armature mmf and rotor are rotating in synchronism or nearly so. The *negative-sequence* reactance x_2 is applicable with an armature mmf rotating backward at synchronous speed while the rotor is rotating forward. Negative-sequence currents arise from certain types of unbalanced operation. The negative-sequence reactance is approximately the average of subtransient reactances

$$x_2 = 1/2(x''_d + x'_q) \quad (7-78)$$

Zero-sequence reactance is applicable to situations in which all 3 phases of the armature have identical currents such as would arise from a ground fault. Such currents do not produce substantial air-gap flux, and even some of the components of armature leakage are reduced, so the zero-sequence inductance is quite small.

7.11.8 Static and Transient Torque-Angle Curves

Torque-angle curves for operation of a synchronous generator may be written for both the synchronous and transient mode of operation. In per-unit these, torque-angle curves are for the steady state case

$$t_e = \frac{e_{af}}{x_d} \sin \delta + \left(\frac{1}{x_q} - \frac{1}{x_d} \right) \sin 2\delta \quad (7-79)$$

and for the transient case

$$t_e = \frac{e'_q}{x'_d} \sin \delta + \left(\frac{1}{x_q} - \frac{1}{x'_d} \right) \sin 2\delta \quad (7-80)$$

where δ is the torque angle, e_{af} is the internal voltage, and e'_q is the voltage behind transient reactance, and the terminal voltage is one per unit.

7.11.9 Stability by Equal Area

The relationship between power, which is directly proportional to torque, and displacement (power) angle is shown in Fig. 7-26. Note that the torque-angle curve for transient operation has a higher peak torque, although the two curves coincide at the steady-state operating point.

Disturbances from steady-state operation due to changes in prime mover torque, load changes, or faults cause load angle to change, usually with dynamic swings as described in this section. Generally, the most serious transient swing results from complete loss of load as from a nearby short-circuit. Under such a circumstance the generator, under the influence of prime mover torque, accelerates. The torque angle increases quadratically with time. Even after the power output is restored, the machine will swing forward until load torque stops its advance. A simple approximate way of estimating the maximum angle achieved is to use the *equal-area* criterion. The area of a disturbance is related to energy contributed to rotation, and for every (stable) situation the positive and negative areas must balance.

Pictured in Fig. 7-26 is a “critical” swing. The area underneath the prime mover torque curve from δ_0 to δ_c is the area that would be contributed if all load torque were zero during a period of acceleration between those two angles. If the area *above* the prime-mover torque between δ_c and δ_f is equal to or greater than this first area, the machine will regain synchronous operation. This establishes a *critical angle*. In turn, the *critical clearing time* t_c is established by

$$\delta_c - \delta_0 = \frac{1}{2} \frac{\omega_0}{2H} t_c^2 \quad (7-81)$$

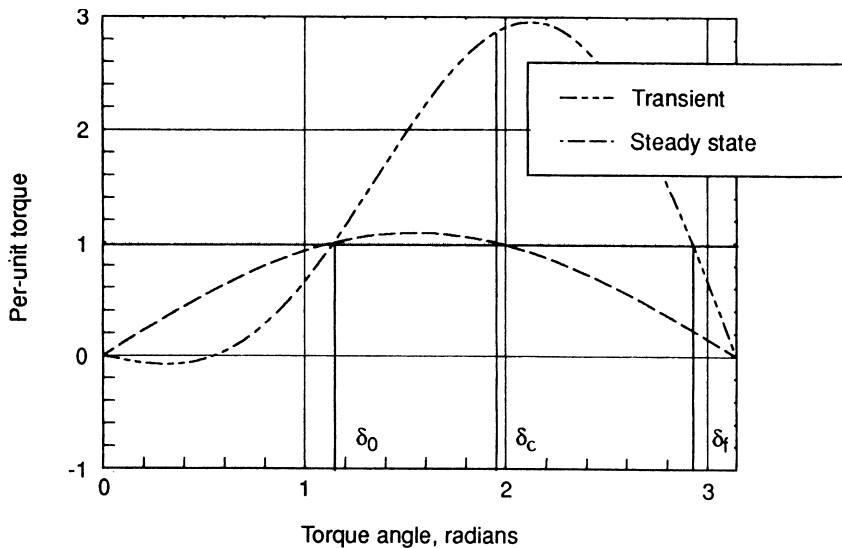


FIGURE 7-26 Torque-angle curves, steady state and transient.

7.11.10 Faults

If an ac generator is operated open-circuited at rated terminal voltage and then its terminals are suddenly short-circuited, the following currents flow in the terminal leads:

$$i_a = \left\{ \frac{e_{af}}{x_d} + \left(\frac{e_{af}}{x'_d} - \frac{e_{af}}{x_d} \right) e^{-(t/T'_d)} + \left(\frac{e_{af}}{x''_d} - \frac{e_{af}}{x'_d} \right) e^{-(t/T''_d)} \right\} \cos(\omega t - \theta_0) - \frac{e_{af}}{x''_d} \cos \theta_0 e^{-(t/T_a)}$$

$$i_b = \left\{ \frac{e_{af}}{x_d} + \left(\frac{e_{af}}{x'_d} - \frac{e_{af}}{x_d} \right) e^{-(t/T'_d)} + \left(\frac{e_{af}}{x''_d} - \frac{e_{af}}{x'_d} \right) e^{-(t/T''_d)} \right\} \cos\left(\omega t - \theta_0 - \frac{2\pi}{3}\right) - \frac{e_{af}}{x''_d} \cos\left(\theta_0 - \frac{2\pi}{3}\right) e^{-(t/T_a)}$$

$$i_c = \left\{ \frac{e_{af}}{x_d} + \left(\frac{e_{af}}{x'_d} - \frac{e_{af}}{x_d} \right) e^{-(t/T'_d)} + \left(\frac{e_{af}}{x''_d} - \frac{e_{af}}{x'_d} \right) e^{-(t/T''_d)} \right\} \cos\left(\omega t - \theta_0 + \frac{2\pi}{3}\right) - \frac{e_{af}}{x''_d} \cos\left(\theta_0 + \frac{2\pi}{3}\right) e^{-(t/T_a)}$$

These currents are shown in Fig. 7-27.

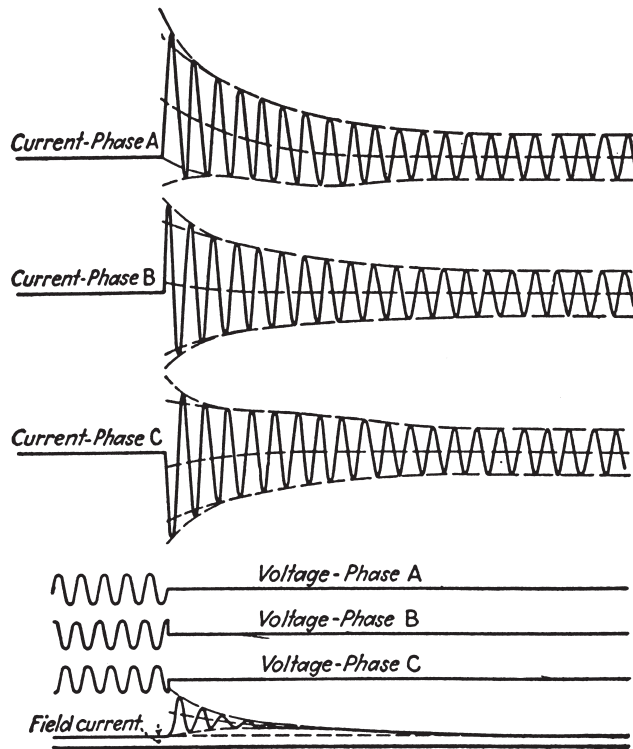


FIGURE 7-27 3-Phase (symmetric) fault currents.

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